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# Simulator Study of a Pictorial Display for General Aviation Instrument Flight

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**NASA**

National Aeronautics  
and Space Administration

Scientific and Technical  
Information Branch

## SUMMARY

A simulation study has been made of a computer-drawn pictorial display in a flight task that included an en route segment, terminal area maneuvering, a final approach, a missed approach, and a hold. All these flight segments were performed under instrument flight conditions in a typical general aviation aircraft. The pictorial display consists of the drawing of boxes which either move along the desired path or are fixed at designated way points. Two boxes may be shown at all times, one related to the active way point and the other related to the standby way point. The flight plan included a short, curved, descending final approach, similar to the type of approach that is made under visual conditions. Ground tracks and vertical profiles of the flights, time histories of the final approach, and pilot comments were obtained from nine subjects.

The results demonstrate the accuracy and consistency with which the en route, terminal area, and final approach segments of the flight are executed. The pilot comments suggest that the display is easy to learn and easy to use, that it provides good situation awareness, and that it could improve the safety of flight. The pilots were critical of the small size of the display, the lack of numerical information on pitch, roll, and heading angles, and the lack of definition of the boundaries of the conventional glide-slope and localizer areas which are delineated by the saturation levels of conventional displays.

## INTRODUCTION

Instruction books such as reference 1 written for general aviation pilots on the subject of instrument flight rule (IFR) flying abound in descriptions of the difficulty and danger of IFR flight. Chapter after chapter is devoted to techniques for properly coordinating aircraft attitudes and displacements, to the difficulty of executing intricate terminal area maneuvers such as procedure turns and holding patterns, and to the dangers of turbulence. Analyses of general aviation accident data, such as that presented in reference 2, reveal that many of these accidents occur under IFR conditions in the terminal area. One of the contributing causes for these accidents is the abstract manner in which conventional instruments display attitude and displacement information about the aircraft to the pilot. The variables that the pilot must coordinate are displayed separately, each with its own separate needle and often its own separate reference point. The difficulty experienced by general aviation pilots, who often are not proficient in the use of these instruments, may be alleviated by providing a more pictorial display, which can be interpreted with greater ease than can conventional displays.

The purpose of this study is to see whether a pictorial display can improve situation awareness, pilot-aircraft system dynamic characteristics, and system performance. The study examines the use of the computer-drawn three-dimensional pictorial display described in reference 3 in a realistic, complete flight. Reference 3 presents the performance obtained with the display in steady state tracking tasks. Reference 4 presents an early concept of the pictorial display. The present study examines the use of the display in a flight which involves an en route segment, terminal area maneuvering, a final approach, a missed approach, and a hold. Nine subjects performed the flights in a fixed-base simulator under IFR conditions.

The oscillatory period of the pilot-aircraft system is a generalized measure of the performance that can be expected from the system. In reference 3, these oscillatory periods were as low as 10 seconds with the pictorial display. These results can be compared with the results presented in reference 5, where the pilot-aircraft system periods with conventional displays were approximately 60 seconds. This comparison suggests that the pictorial display can be used to execute a much tighter flight pattern than can be performed with conventional displays. In the present study, the pictorial display is used to make an approach pattern that is similar to the one used under visual flight conditions, as opposed to the much longer approach used under instrument flight conditions with conventional displays.

Since the precision with which the aircraft must be positioned while en route is much less than that required during a final approach, the pictorial display was adjusted throughout the flight to suit the different flight segments. Further adjustments were made to meet the requirements for terminal area maneuvering and for holding patterns. Ground tracks and vertical profiles of the flights, time histories of the final approach, and pilot opinions were obtained to determine the suitability of the pictorial display.

#### SYMBOLS

$C$	box center position
$G_u, G_v, G_w$	gust spectrum transfer functions
$h$	altitude, m
$i, j, k$	unit vectors
$K_\ell, K_g$	scaling factors
$L_u, L_v, L_w$	gust characteristic wavelengths, m
$\ell_x, \ell_y, \ell_z$	semilengths of box edges, m
$p, q, r$	roll, pitch, and yaw angular rates, rad/sec
$s$	Laplace operator, $\text{sec}^{-1}$
$T_A, T_V$	transformation matrices
$u_g, v_g, w_g$	orthogonal random gust components, m/sec
$u_i, v_i, w_i$	inertial components of wind velocity, knots
$V$	aircraft velocity, m/sec
$X, Y, Z$	aircraft body-axis system
$x, y, z$	way-point coordinates in navigation axis system, n.mi.
$x_i, y_i, z_i$	inertial axes
$x_{iA}, y_{iA}, z_{iA}$	aircraft inertial position, m

$x_{iB}, y_{iB}, z_{iB}$  box inertial position, m  
 $\alpha, \beta$  angle of attack and sideslip, rad  
 $\sigma_u, \sigma_v, \sigma_w$  gust amplitudes, m/sec  
 $\psi, \theta, \phi$  Eulerian angles, rad

Nondimensional stability derivatives:

$C_{L_{\delta_e}}$  lift coefficient due to elevator deflection  
 $C_{l_{\beta}}$  rolling-moment coefficient due to sideslip  
 $C_{n_{\beta}}$  yawing moment due to sideslip  
 $C_{n_{\delta_a}}$  yawing moment due to aileron deflection  
 $C_{Y_{\beta}}$  side-force coefficient due to sideslip

Abbreviations:

CDI course deviation indicator  
 CRT cathode ray tube  
 DME distance measuring equipment  
 FTE flight technical error  
 HSI horizontal situation indicator  
 IFR instrument flight rules  
 ILS instrument landing system  
 MLS microwave landing system  
 PIO pilot-induced oscillations  
 RNAV area navigation  
 VOR very high frequency omnirange

Subscripts:

A aircraft  
 B box

BA box minus aircraft

p picture

V visual

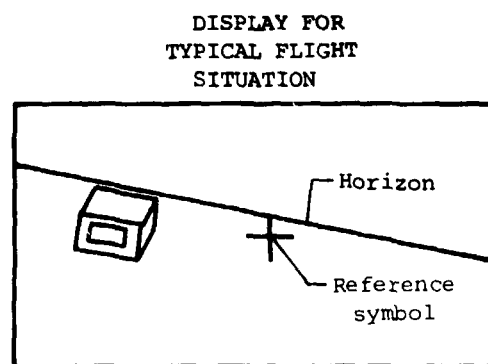
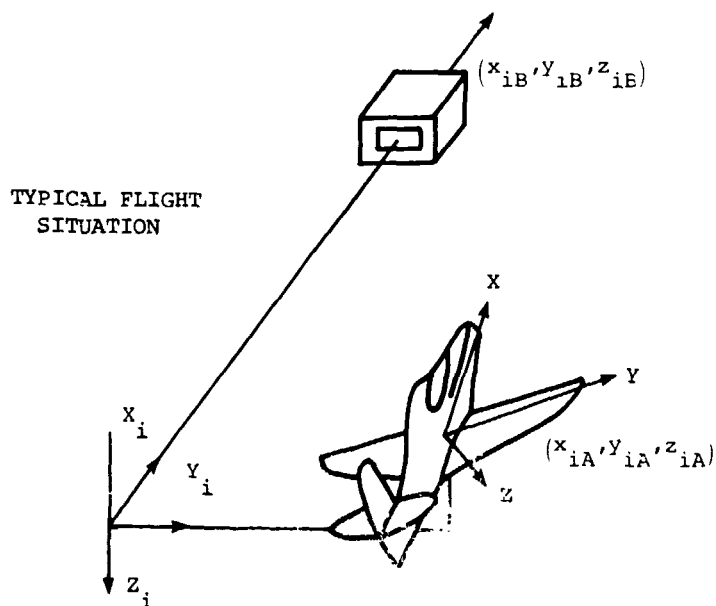
W window

Superscripts:

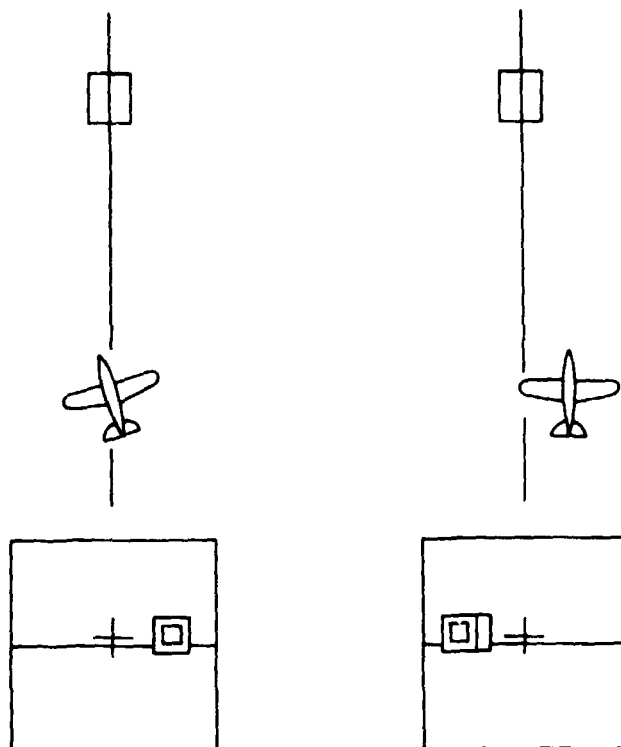
x,y,z associated with designated axis

#### DISPLAY CONCEPT AND DESCRIPTION

The display consists of a drawing presented on a cathode ray tube (CRT) of a three-dimensional box which basically is located on and aligned with the desired path, and moves along the path ahead of the aircraft. The pilot's task is to follow the box. A typical situation is shown in sketch A. The display can be generated from the following parameters: values of  $x_{iB} - x_{iA}$ ,  $y_{iB} - y_{iA}$ , and  $z_{iB} - z_{iA}$ ; the attitude of the aircraft; the attitude of the box; specification of the box size; and a selected field of view. The display for the flight situation in sketch A would appear as shown in sketch B.



To illustrate the information content of the display, consider the simplified lateral situations shown in sketch C. A heading error alone (no displacement error) results in the display shown on the left, with the box displaced from the aircraft reference symbol. A displacement error alone (no heading error) also causes the box to be displaced from the aircraft reference symbol, but with the side of the box visible (right side of sketch C). Placing the aircraft reference symbol on the near face of the box results in a heading angle that will eliminate the displacement error. As the displacement error is reduced, the side of the box disappears. Thus, both flight director data and raw displacement data are provided by the display.



Sketch C

Selected values of  $x_{iB} - x_{iA}$  are used to meet the various control requirements for different segments of the flight. The changes in this parameter are discussed in detail in the following sections. The algorithm used to draw the display picture is presented in appendix A.

#### Approach

For the final approach segment of the flight the orthogonal distances from the aircraft to the box are obtained from the instrument landing system in the following manner:

$$y_{iB} - y_{iA} = K_L(\text{Localizer signal})(\text{Range to station})$$

$$z_{iB} - z_{iA} = K_G(\text{Glide-slope signal})(\text{Range to station})$$

$$- (x_{iB} - x_{iA}) \tan(\text{Glide-slope angle})$$

$$x_{iB} - x_{iA} = \text{Selected value}$$

The localizer and glide-slope signals are the conventional angular landing system signals. These signals are multiplied by the range to the station and appropriate scaling factors so that a true geometric view of the box can be drawn. In the simulation, the computed aircraft position and attitude angles were used to generate noise-free signals.

It is assumed that the landing system provides good signals throughout a wide field, as is the case with a microwave landing system (MLS). It is therefore possible, for example, for an aircraft which is 3 n.mi. from touchdown and 3 n.mi. to the side of the localizer to receive the data required to draw the picture. If the aircraft is at an altitude that is approximately equal to the height of the glide slope and is pointed approximately normal to the localizer, then the box is drawn in view. Pointing directly at the box results in the aircraft making a smooth entry onto the final approach path. This is the type of approach that was performed in the study.

The selected value of  $x_{iB} - x_{iA}$  is the dominant factor in determining the radius of curvature of the final turn and the precision with which the aircraft follows the glide-slope localizer path. A value for  $x_{iB} - x_{iA}$  of 368 m was used. The aircraft model used in the simulation represented an aircraft with an approach speed of 100 to 86 knots. With this aircraft and  $x_{iB} - x_{iA} = 368$  m, it was anticipated that the final turn could be made with a maximum bank angle of  $20^\circ$ . It was also anticipated that the approach path would be precise enough so that a decision height of 30 m could be used. For these reasons the value of 368 m for  $x_{iB} - x_{iA}$  was selected.

The complete specifications of the input data to the display algorithm for the final approach phase of the flight is as follows:

#### Approach

$$x_{iB} - x_{iA} = 368 \text{ m}$$

$$y_{iB} - y_{iA} = K_L(\text{Localizer signal})(\text{Range to station})$$

$$z_{iB} - z_{iA} = K_G(\text{Glide-slope signal})(\text{Range to station}) \\ - 368 \tan(\text{Glide-slope angle})$$

$$\psi_B = 0, \quad \phi_B = 0, \quad \theta_B = \text{Glide-slope angle}$$

$$\phi_A = \text{Aircraft heading} - \text{Runway heading}$$

$$\phi_A = \text{Aircraft bank angle}$$

$$\theta_A = \text{Aircraft pitch angle}$$

Box size: 61 m  $\times$  30.5 m  $\times$  15 m

Field of view:  $\pm 45^\circ$



## En Route

For the en route segment of the flight, called the "long line" segment on the display, an area navigation (RNAV) program in conjunction with a very high frequency omnirange distance measuring equipment (VOR-DME) station signal is used to determine the position of the aircraft. The position of the aircraft relative to the station is translated and rotated to provide the position of the aircraft (x,y) relative to the selected way point in an axis system aligned with the selected radial to the way point. The aircraft lateral error,  $y_{iB} - y_{iA}$ , is thereby determined. The vertical error is determined through the use of an altimeter and a selected altitude. Since precise positioning of the aircraft is not required en route, but ease of capture and following of the box is very important, a value of 4 n.mi. was chosen for  $x_{iB} - x_{iA}$ . This value remains in effect until the aircraft is 4 n.mi. from the way point. At this point, the distance from the aircraft to the way point is used for  $x_{iB} - x_{iA}$  instead of the fixed 4-n.mi. value. This arrangement makes it easy for the pilot to acquire the box and follow it along the en route segment of the flight. As the aircraft approaches the way point, the pilot observes a gradual increase in the size of the box on the display.

The complete specification of the input data for the en route, or long line, segment of the flight is as follows:

### En Route

$$x_{iB} - x_{iA} = \begin{cases} 7400 \text{ m} \\ \text{(When aircraft is more than 4 n.mi. from way point)} \\ x \text{ from RNAV program} \\ \text{(When aircraft is less than 4 n.mi. from way point)} \end{cases}$$

$$y_{iB} - y_{iA} = y \text{ from RNAV program}$$

$$z_{iB} - z_{iA} = \text{Aircraft altitude} - \text{Selected altitude}$$

$$\phi_B = 0, \quad \phi_B = 0, \quad \theta_B = 0$$

$$\phi_A = \text{Aircraft heading} - \text{Selected bearing to way point}$$

$$\phi_A = \text{Aircraft bank angle}$$

$$\theta_A = \text{Aircraft pitch angle}$$

$$\text{Box size: } 1830 \text{ m} \times 610 \text{ m} \times 244 \text{ m}$$

$$\text{Field of view: } \pm 45^\circ$$

## Stationary Box

The en route and final approach segments of the flight do not, in general, match in either altitude, lateral position, or heading. This adjustment in flight path between these two segments is usually not large enough to use the en route program. To accommodate these situations, stationary boxes are used. The stationary box forms a gate for entry to the next flight segment. The RNAV program is used to determine

the position of the aircraft with respect to the gate in an axis system aligned with the direction that the aircraft should move through the gate. Consideration of the geometry involved shows that stationary boxes do not provide the same kind of flight director (lead) information that the moving boxes do, and therefore the aircraft positioning is not as precise with the stationary boxes as with the moving boxes.

The complete specification of the input data for stationary boxes is as follows:

#### Stationary

$x_{iB} - x_{iA} = x$  distance from stationary way point

$y_{iB} - y_{iA} = y$  distance from stationary way point

$z_{iB} - z_{iA} = \text{Aircraft altitude} - \text{Selected altitude}$

$\psi_B = 0, \phi_B = 0, \theta_B = 0$

$\psi_A = \text{Aircraft heading} - \text{Selected heading of box}$

$\phi_A = \text{Aircraft bank angle}$

$\theta_A = \text{Aircraft pitch angle}$

Box size: 915 m x 153 m x 153 m

Field of view:  $\pm 45^\circ$

#### Two Box Format

To use these different types of box configuration for different flight segments requires switching from one box to another. Two boxes are drawn at all times, so that a secure transfer from one box to the next can be made. One box is the current (active) box, and the second is the next (standby) box. In most instances, the standby box is visible along with the active box. Before it is necessary to turn to the standby box, time is available to cross-check with the aeronautical chart or approach chart, to verify that the standby box is in the expected relative position, and to prepare to turn to it. To assist in distinguishing between the two boxes, the standby box is drawn with dashed lines in contrast to the solid lines used for the active box.

#### Holding Pattern

The availability of two boxes lend itself to providing additional guidance for holding patterns. This guidance is obtained by the simple push of a button. When the holding pattern is called for, the standby box is drawn 4 n.mi. ahead and 1.1 n.mi. either right or left of the active box. The standby box then provides position information for the outbound leg of the holding pattern. This information simplifies entries into the holding pattern and assists in establishing a consistent pattern. The specifications for the holding box are completely defined relative to the active box, so that the RNAV computer can automatically generate the holding box whenever the pilot pushes the hold button.

The complete specification of the input data for holding patterns is as follows:

#### Holding Pattern

$$x_{iB} - x_{iA} = (x_{iB} - x_{iA}) \text{Active way point} - 7400 \text{ m}$$

$$y_{iB} - y_{iA} = \begin{cases} (y_{iB} - y_{iA}) \text{Active way point} + 2130 \text{ m} & \text{(For hold right)} \\ (y_{iB} - y_{iA}) \text{Active way point} - 2130 \text{ m} & \text{(For hold left)} \end{cases}$$

$$z_{iB} - z_{iA} = (z_{iB} - z_{iA}) \text{Active way point}$$

$$\phi_B = 0, \quad \phi_B = 0, \quad \theta_B = 0$$

$$\phi_A = \text{Aircraft heading} - \text{Way-point heading} + 190^\circ$$

$$\phi_A = \text{Aircraft bank angle}$$

$$\theta_A = \text{Aircraft pitch angle}$$

Box size: Same as active way point

Field of view:  $\pm 45^\circ$

#### Example Flight Plan

To examine how the different display configurations and the switching logic would apply to a flight task, an example flight involving all the previously discussed flight segments was devised. This flight plan called for a flight to Norfolk International Airport from the northwest with a landing on runway 05. The approach chart used is shown in figure 1. The procedure was to approach way point Sussex on a  $136^\circ$  radial using the en route display configuration. After arriving at Sussex, a sidestep to the right and a change in altitude to Gate 1, a stationary box, was called for. By flying through Gate 1, the pilot reached a position from which he could acquire the final approach box. A  $90^\circ$  turn was then executed to the final approach. A stationary go-around box called Exit was also scheduled to be used if a missed approach was required. The go-around box would guide the pilot for a return to Sussex where procedures called for a hold until another attempt at landing could be made. The complete flight is illustrated with the panoramic view shown in figure 2.

The RNAV way-point list for this flight was as follows:

1. Sussex
2. Gate 1
3. Approach
4. Exit

At the start of the flight, Sussex was active and Gate 1 standby. An advance button was provided in the cockpit for progression through the way-point list at the pilot's

discretion. When the pilot was finished with Sussex, pushing the advance button removed Sussex from the computer program, made Gate 1 active, and brought up the approach box as standby. A message in the lower left corner of the display announced which way point was active. Pushing the advance button again made the approach box active and Exit standby. The next advance made Exit active, and the progression recycled to the beginning of the list to make Sussex standby. Two hold buttons, right and left, were also provided for calling for the holding display.

The message presented on the display also showed the type of configuration being used (long line, stationary, approach, or hold) in addition to the name of the active way point. Also shown on the display was an aircraft reference symbol in the form of a cross and horizon line. The aircraft reference symbol was fixed with respect to aircraft motion, but was adjustable up and down at the pilot's command so that it could be matched to the aircraft steady state velocity vector. However, in the present study a cockpit control for this adjustment was not available, and the symbol was set to match the steady state velocity vector for the 100 knot clean condition, and it remained in that position throughout the flight simulation.

#### RNAV Input Data

To implement this flight plan, the pilot had to insert the following data on way-point position, display configuration, and navigation data source in the RNAV program. These data are stored in units, called pages (see table I), so that the logic for moving from one to the next could be implemented.

TABLE I.- RNAV PAGES

Page 1					
Way point	<u>Sussex</u>	Receiver	<u>1</u>	Frequency	<u>116.9 MHz</u>
Type	<u>Long Line</u>				
x = <u>0</u>	y = <u>-4.0 n.mi.</u>	z = <u>2000 ft</u> (610 m)	$\phi = $	<u>136°</u>	$\theta = $
				<u>0°</u>	
Page 2					
Way point	<u>Gate 1</u>	Receiver	<u>1</u>	Frequency	<u>116.9 MHz</u>
Type	<u>Stationary</u>				
x = <u>-3.0 n.mi.</u>	y = <u>-1.0 n.mi.</u>	z = <u>1000 ft</u> (305 m)	$\phi = $	<u>136°</u>	$\theta = $
				<u>0°</u>	
Page 3					
Way point	<u>MLS</u>	Receiver	<u>2</u>	Frequency	<u>109.1 MHz</u>
Type	<u>Approach</u>				
				$\phi = $	<u>46°</u>
					$\theta = $
				<u>-3°</u>	
Page 4					
Way point	<u>Exit</u>	Receiver	<u>1</u>	Frequency	<u>116.9 MHz</u>
Type	<u>Stationary</u>				
x = <u>1.0 n.mi.</u>	y = <u>-1.0 n.mi.</u>	z = <u>1000 ft</u> (305 m)	$\phi = $	<u>316°</u>	$\theta = $
				<u>0°</u>	

The way-point locations (x,y,z) are given relative to the runway touchdown point in an axis system that is aligned with the runway in this study. An input device for inserting the data was not available in the simulator, so these data were inserted as a part of the simulator program. The pilots were required to list the data on a sheet of paper before the tests started to fix the flight plan in their minds.

Two photographs of the display, one as the aircraft is leaving Sussex and the other as the aircraft is entering the final approach, are shown in figures 3 and 4.

## EXPERIMENTS

The tests were conducted in a fixed-base cockpit, shown in figure 5, which was driven by a large capacity digital computer. Nine subjects took part. Information on the subjects, the simulator, the wind inputs used in the tests, and the test procedures follows.

### Subjects

The subjects that took part in the study are listed in table II with some information on their experience. All subjects except 7 are instrument rated (subject 7 is in the process of obtaining his rating and the ratings of subjects 3 and 5 were not current). Subjects 8 and 9 are NASA test pilots. Most of the subjects had no previous experience with the display (subjects 7 and 9 took part in the study of ref. 3). Three of the subjects had no previous experience with the particular simulator used in this study, although all had some previous experience with research simulators.

TABLE II.- SUBJECT PILOTS' EXPERIENCE

Subject	Age	Flight hours	Current IFR rating	Previous experience with display	Previous experience with simulator
1	23	300	Yes	No	Yes
2	54	300	Yes	No	Yes
3	45	360	No	No	Yes
4	32	1200	Yes	No	Yes
5	37	1400	No	No	No
6	41	1600	Yes	No	Yes
7	44	2500	No	Yes	Yes
8	40	2600	Yes	No	No
9	39	5500	Yes	Yes	No

The subjects were given a half-hour briefing on the operation and procedures of the display system. They were told that with the moving boxes, a smooth correction of any position error would result if they placed the aircraft reference symbol on the center of the box. For vernier adjustment when the error was small, and in the presence of cross winds or longitudinal trim change, it became necessary to adjust the aim point slightly. Subjects 2, 3, and 4 were given a short demonstration on the use of the display. The rest were given no demonstration. With this brief introduction all subjects proceeded to execute the flight.

## Simulator

Using six-degree-of-freedom, nonlinear equations of motion, the simulator modeled a typical, high wing, four passenger, single engine general aviation aircraft. In addition to nonlinear kinematics, the following nonlinear aerodynamic factors and other special features were included in the simulation:

1. Nonlinear lift and drag coefficients were a function of  $\alpha^2$  as well as  $\alpha$ .
2. Nondimensional stability coefficients  $C_{Y_\beta}$ ,  $C_{L_{\delta_e}}$ ,  $C_{l_\beta}$ ,  $C_{n_{\delta_a}}$ , and  $C_{n_\beta}$  were a function of  $\alpha$ .
3. Asymmetric forces and moments as a function of thrust coefficient were included.
4. A hydraulic control loader provided control forces as a function of aerodynamic hinge moments.
5. A sound system provided realistic engine and airstream noise.

The dynamic responses of the simulator model aircraft to step control inputs at two airspeeds (135 and 85 knots) are shown in figures 6 and 7. Figure 6(a) shows the short-period longitudinal response to a 0.02-rad elevator step input. The response is well damped with frequencies of 6 rad/sec at 135 knots and 2 rad/sec at 85 knots. The phugoid response to an initial out-of-trim angle of attack, shown in figure 6(b), is stable with periods of 55 and 30 sec. The lateral dynamic response, shown in figure 7, is fairly well damped with frequencies of 3 and 2 rad/sec. Figure 7 also shows the large effect of the adverse yaw which was included in the aircraft model.

The display was presented on a 7.6 cm  $\times$  10.16 cm CRT mounted in the center of the instrument panel, as shown in figure 5. Also included in the instrument panel were airspeed and altitude indicators, which the pilot had to use. For cross-checking, a turn and bank, a rate-of-climb, and a horizontal situation indicator were present. A course deviation indicator was present, but was not tuned to the destination airport.

An out-the-window display was also present in the simulator. The display was produced by moving a television camera system over a ground terrain model which included an airport. The picture that resulted was displayed on a large picture tube mounted in the windscreen of the cockpit. This picture had a field of view of  $\pm 20^\circ$  laterally and  $+20^\circ$ ,  $-10^\circ$  vertically. Further information on this out-the-window display is presented in reference 6. Variable meteorological conditions could be imposed on the out-the-window picture. In this study a visibility range of 1 n.mi. and a ceiling of either 27.5 or 36.6 m above ground was used. The simulator model also included landing gear reactions so that a realistic touchdown and roll-out could be performed.

## Wind Inputs

In some of the tests, wind inputs were included. These wind inputs were a combination of wind shears and random gusts. The random gust inputs had three orthogonal components -  $v_g$ ,  $u_g$ , and  $w_g$  - which were generated using a random number generator and filters based on the Dryden gust model (ref. 7). The filters were

$$G_u(s) = \sigma_u \frac{1}{s + \frac{v}{L_u}}$$

$$G_v(s) = \sigma_v \frac{s + \frac{1}{\sqrt{3}} \frac{v}{L_v}}{\left(s + \frac{v}{L_v}\right)^2}$$

$$G_w(s) = \sigma_w \frac{s + \frac{1}{\sqrt{3}} \frac{v}{L_w}}{\left(s + \frac{v}{L_w}\right)^2}$$

The scale lengths were

$$L_u = L_v = \begin{cases} h & (\text{For } h \geq 535 \text{ m}) \\ 44h^{1/3} & (\text{For } h < 535 \text{ m}) \end{cases}$$

$$L_w = h$$

The amplitudes of the gust components  $\sigma_u$ ,  $\sigma_v$ , and  $\sigma_w$  were adjusted so that the root mean square of the gusts was either 0.61 or 1.21 m/sec at 535 m altitude.

Two different wind shears were used. Each of these wind shears was defined throughout the region of flight. The values of the wind velocity components along the nominal final approach path are presented in figure 8. The first, which was called a nighttime stable condition, was combined with the 0.61 m/sec random gust. The second, which was called a moderate thunderstorm condition, was combined with the 1.21 m/sec random gust.

#### Test Procedures

Each subject made four flights, the first two with no winds, followed by one flight with each of the two wind conditions. Each flight was started at an altitude of 610 m, 1.2 n.mi. to the left of the en route course, with the aircraft trimmed for level flight at 100 knots. The first flight was started with the aircraft headed 230°, which meant that the box for way point Sussex was not in the field of view. The pilot had to maneuver the aircraft to find the box. All the rest of the flights except for one were started with the aircraft headed at 136°, but 1.2 n.mi. to the left of the desired course, with the en route box in view.

At the completion of the four flights with the box display, each subject made one or two flights with conventional displays for comparison. In these flights the pilot flew an 85° radial from a nearby VOR station, using the course deviation indicator (CDI), in order to intercept the destination MLS station with a 45° intercept angle at a point 3 n.mi. from touchdown. This is not a standard approach, but is one that roughly corresponds to the approach flown with the box display. The horizon on the CRT was used for an attitude indicator in these flights.

The pilot was alone in the simulator during the tests. The experimenter acted as an air traffic controller, representing, in turn, departure control, approach control, and tower control. Departure control instructed the pilot to proceed as filed. Approach control confirmed that the pilot could make a special RNAV approach via Sussex and Gate 1. Tower control gave the airport weather and clearance for landing and other instructions as required by the tests. All pilot inquiries were answered.

## RESULTS

### Related Results From Previous Studies

As was noted in the Introduction, the pilot-aircraft-display system has a higher dominant frequency with the box display than with conventional displays. Figure 9 further illustrates this point. Shown are the frequency and damping of the dominant oscillatory mode of motion of the lateral response. These systems also contain higher frequency modes, but they are of only minor consequence in the lateral position output of the systems. The data points are for different sensitivities of the displacement signals of the displays. For the conventional displays (as presented on either a CDI or a horizontal situation indicator (HSI)), these differences result from being at various ranges from the station, and for the box display, they result from being at various distances from the box. The data are from references 3 and 5. Also shown are a few data points obtained from the use of a three-axis attitude indicator with cross pointers, taken from references 3 and 8.

As can be seen from figure 9, the system frequencies with the box display are higher than those with the three-axis attitude indicator; and the system frequencies with the three-axis indicator are higher than those with conventional displays. This progression in system frequency correlates with the degree of integration of the signals required for stable control of the aircraft lateral response. In order to have good control of lateral displacement, the pilot must also control bank angle and heading angle. With conventional displays, these three quantities are displayed in separate locations on the instrument panel; with the three-axis indicator, they are grouped close together; and with the box display, they are all shown with the one symbol. As a result of this integration of information and the resulting high system frequency, the box display can be used to execute a much tighter flight pattern (involving short segments and sharp turns) than can be performed with conventional displays. The present study demonstrates these features of the display.

### Results From Present Study

A typical ground plot and vertical profile, obtained from the first flight of subject 4, is shown in figure 10. The aircraft was initially headed so that the box was not in the field of view. The subject initially turned in the wrong direction to acquire the box and had to turn 300° to do so. The plot illustrates the system response that is to be expected in correcting lateral displacement errors in the en route segment of the flight. The altitude profile shows that the desired altitude is maintained within 10 m. The ground plot also illustrates the stable acquisition of the final approach, with no overshoot in this particular case. On the first final approach, the ceiling was set at 27.5 m above ground. The subject flew down to the decision height of 30.5 m and performed a missed approach. The subject returned to way point Sussex, entered the holding pattern on the outbound leg, and proceeded to hold. The second time he was outbound he was given clearance to land, and he pro-



ceeded with a second approach. During the second approach, the ceiling was set at 36.6 m, and the subject performed a good touchdown and roll-out.

Not all subjects were as successful on their first flights as subject 4. Subject 5 seemed to have the greatest difficulty in using the display. A ground plot and altitude profile of subject 5's first flight is shown in figure 11. He got through Gate 1 in reasonable fashion. Up until this point in the flight the standby box always appeared to be smaller than the active box because the standby box was smaller and farther away. When the final approach box became active and Exit became standby, both boxes appeared to be the same size, because the Exit box was bigger than the final approach box and was not much farther away. This situation confused subject 5 and his first approach was not carried out properly. The subject requested a restart when he realized his mistake. His second final approach was completed competently. Since the ceiling was 27.5 m, the pilot performed a missed approach.

The missed approach involved complex procedures, involving the proper sequencing of the advance and hold buttons. The holding pattern procedures were also different from normal holding procedures. Position information was presented on the outbound leg as well as on the inbound leg, in contrast to the normal situation where position information is available only on the inbound leg. Subject 5, as well as subjects 3, 7, and 9, had difficulty in adjusting to the increased amount of information available with the box display during holding procedures. As can be seen from figure 11, subject 5 turned in the wrong direction at the conclusion of his outbound leg. After the air traffic controller asked what his intentions were, he corrected his mistake. He returned to the holding pattern, was given a clearance to land on his second outbound leg, and completed the approach.

A composite of the ground tracks of the first flights of five subjects is shown in figure 12. This figure is shown to illustrate the spread in ground tracks obtained with different subjects. All of the subjects except for subject 5 were able to complete the initial approach in a reasonable manner. All but one observed the decision height criterion and performed missed approaches when the ceiling was at 27.5 m. Subject 6 turned away from Sussex earlier than did the others. All the rest of the subjects continued toward Sussex until they were inside the box and then turned toward Gate 1. There were some differences in entries into the holding pattern, but once in the holding pattern, all subjects flew very similar patterns.

The combined ground tracks of the first flights of the three subjects that were given a demonstration of the use of the display before their first flight are shown in figure 13. The flight patterns for these subjects are consistent, with the greatest variations occurring in the transfer from Sussex to Gate 1. In all cases, a very stable and precise final approach was executed.

To examine the final approach more closely, time histories of glide-slope and localizer errors for subjects 4 and 5 are presented in figures 14 and 15. The figures show that localizer and glide slope are stably acquired and that the errors are held to small values. It is felt that subject 4 demonstrated exceptionally good control for a pilot who had no previous experience with the display. The 3 n.mi. that were allowed for the final approach were more than adequate. The ground tracks previously discussed and these time histories show that the display, in conjunction with a wide coverage landing system such as an MLS, makes curved descending approaches possible.

Breakout (emergence from cloud ceiling), touchdown, and the lateral boundaries of the runway are also shown in figures 14 and 15. The time histories show that the

dynamic response characteristics of the pilot-aircraft system change noticeably after breakout when the runway becomes visible to the pilot.

A composite of the ground tracks for seven subjects on their second flight is shown in figure 16. These flights were started with the en route box in view, but with the aircraft displaced 1.2 n.mi. from the desired radial. The flights also contained an emergency hold at Gate 1, which was announced by the air traffic controller as the pilots made their turn toward Gate 1. The ground tracks in this figure illustrate the pilot-aircraft system response on the en route segment of the flight clearer than the ground tracks for the first flight. The response is very stable, but slow. Also shown is the consistency of the holding patterns that can be obtained with the display and, again, the precise control of the final approach.

A composite of flight tracks for all nine subjects made in the presence of the nighttime stable wind condition (20 to 25 knots from 050°) are shown in figure 17. Subject 1 was inadvertently given initial conditions similar to those used in the first flight. Also, one subject turned away from Sussex sooner than did the others. Overall, there is no evidence of steady state error due to the wind. All but subject 7 adjusted the aim point when approaching Sussex and Gate 1 in order to remain on course. These subjects also kept the aircraft symbol on the final approach box after leaving Gate 1 and made normal turns onto the final approach. Subject 7, who did not use these techniques, was moved off course on the base leg by the wind, but nevertheless made a turn onto the final approach with no overshoot.

The ceiling was set at 27.5 m for the initial approach in this flight. Subjects 7, 8, and 9 descended below decision height and made good landings. The other six subjects performed missed approaches and returned to Sussex. Subject 3 entered the holding pattern on the inbound leg after performing a misshaped teardrop entry. The remaining subjects entered the holding pattern on the outbound leg. They were given clearance to land as soon as they were established on the outbound leg, and all cut the holding pattern short and proceeded with the second approach. The ceiling was set at 36.6 m for the second attempt, and all made good landings.

Ground tracks for the nine subjects in the presence of the moderate thunderstorm wind condition (variable winds up to 35 knots) are shown in figure 18. The ceiling in these flights was at 36.6 m. In spite of the severe wind condition, seven of the subjects made good landings. Subject 6 chose to take off again and repeat the approach. Two of the subjects, 3 and 5, broke out of the overcast and saw the runway, but were not satisfied with their alignment and made missed approaches. Subject 3 returned to Sussex, was given a clearance for landing, and made a successful landing on his second attempt. Subject 5 became confused and started toward Gate 1 after leaving Exit. When he was warned by air traffic control that he was departing from course, he corrected his mistake and made a good approach and landing after a proper hold.

Sample time histories of glide-slope and localizer errors for the final approach with the moderate thunderstorm wind condition are presented in figures 19 and 20. These records illustrate the control precision that is exercised in the presence of this severe wind condition. The subjects did make good landings on the runway.

To further illustrate the precision of control that is obtained with the box display, time histories of final approaches made with conventional displays are presented in figures 21 through 24 for comparison. These runs were made with a 45° intercept of the final approach 3 n.mi. from the touchdown point. The HSI was used for position and heading information, and the horizon and aircraft symbol on the CRT

were used for pitch and roll attitude information. Flights with no winds are shown in figures 21 through 23. In these tests, two of the subjects never acquired the glide slope (they flew completely through the glide slope) and therefore were unable to make an approach. The other subjects did make landings. The approach executed by subject 8 (fig. 21) is a very illustrative example of the type of approach made with conventional instruments. At the intercept point a very long-period (approximately 50 sec) lateral response is generated, along with a very slow, asymptotic vertical response. As the range to touchdown decreases, an instability in the lateral response begins to develop. At breakout, the pilot has to contend with a misalignment in heading. In this case he succeeds in correcting this misalignment and makes a landing. Most of the subjects experienced such difficulties. An approach with conventional instruments by subject 5, shown in figure 22, is another example. It should be noted that subject 5's instrument rating was not current. Subject 4 performed the best approach with conventional instruments. His attempt is shown on figure 23, and depicts a stable but slow capture of the approach path.

Subject 4 also performed an approach with conventional instruments in the presence of the moderate thunderstorm wind condition. This run is presented in figure 24 and can be compared with figure 19 which shows the results obtained with the box display. With the box display, the approach path is acquired well before breakout, and no correction is required after breakout. With the conventional display a stable steady state condition is never reached, and a correction has to be made after breakout. The contrast between the results obtained with the box display and conventional display illustrates the advantages provided by the higher system frequency obtained with the box.

In addition to the ground plots and time histories, pilot comments were also obtained during the study. The answers given by the subjects to specific questions are presented in appendix B.

Because of the limited amount of testing done in this study, the subjects were not able to reach a firm conviction related to the accuracy of the control on the final approach. However, the time histories show the precision with which the final approach was executed. In many instances, the subjects noted that the two-box format provided good situation information. Several subjects also noted that very little practice was required to reach an acceptable level of performance. The pilots felt that the display would increase the safety of single pilot operations. Negative comments about the display were related to its small size, the lack of numerical data on pitch, roll, and heading angles, and the lack of definition of the size of the glide-slope and localizer areas of coverage that are delineated by the saturation levels of conventional displays.

The last point raised in the comments is hardest to resolve. One of the advantages of the box display is that it provides useful information when the aircraft is in a position that would saturate a conventional localizer or glide-slope indicator. As a result the subjects noted the good situation information that was provided. This factor is also the reason that the box display could take advantage of the wide field signal provided by an MLS system. It would therefore seem to be counterproductive to limit the information presented by the box display to be equivalent to conventional displays. It does seem, though, that some additional information on vertical error is called for. Since the active band on the glide-slope indicator of a conventional display is used to define an area that is guaranteed to be free of obstacles, it may be beneficial to include a glide-slope indicator in the CRT display along with the box so that the pilot would be warned if he developed a vertical error outside the normal glide-slope indicator range.

#### CONCLUDING REMARKS

A simulation study has been conducted of instrument flight using a pictorial display in an advanced navigation and guidance system. Both en route and terminal area tasks were examined. A general aviation class aircraft, flown by nine different pilots, was simulated. The display consisted of a drawing of three-dimensional boxes aligned with the desired flight path. The pilot's task was to follow the boxes. It was assumed that the system included a microwave landing system, distance measuring equipment, a computer for executing an area navigation program and the algorithms for drawing two boxes, a cathode ray tube presenting the pictorial display, and conventional navigation and aircraft attitude measuring equipment.

The results show that the parameters of the display can be adjusted so that the display is very easy to use en route, so that terminal area maneuvering can be accomplished with good situation awareness, and so that a short, curved, descending final approach can be executed with precise control. A decision height of only 30 m was used with no control difficulties.

The subjects commented that the display was easy to use, that it provided good situation awareness, and that it would increase safety of flight for single pilot operations. Negative comments were related to the small size of the display, the lack of numerical data on pitch, roll, and heading angles, and the lack of warning if flight path errors should exceed values that saturate conventional glide-slope and localizer indicators.

Langley Research Center  
National Aeronautics and Space Administration  
Hampton, VA 23665  
January 25, 1982

## APPENDIX A

### DERIVATION OF EQUATIONS FOR DISPLAY ALGORITHM

The equations used to define the display images of the boxes are presented in this appendix. The following development is taken from reference 3. The symbols used in this appendix are defined in the main body of this report.

Imagine that a rectangular box-shaped object is located in space in the vicinity of the aircraft as shown in sketch A on page 4. The projection of the object that the pilot would see through the window can be mathematically described. This mathematical description can then be used to form an image on an electronic display device which would reproduce the pilot's view.

The center of the box is located at a position designated by  $(x_{iB}, y_{iB}, z_{iB})$  in inertial coordinates. Vectors that define the size of the box are obtained by multiplying semilengths  $\lambda_x$ ,  $\lambda_y$ , and  $\lambda_z$  by orthogonal unit vectors  $i$ ,  $j$ , and  $k$ :

$$i_B = i\lambda_x$$

$$j_B = j\lambda_y$$

$$k_B = k\lambda_z$$

If the box is at an attitude  $\phi_B$ ,  $\theta_B$ , and  $\psi_B$  to the reference inertial-axis system, then the inertial components of the box vectors are

$$i_i = \begin{bmatrix} i_i^x \\ i_i^y \\ i_i^z \end{bmatrix} = \begin{bmatrix} i_B(\cos \theta_B \cos \phi_B) \\ i_B(\cos \theta_B \sin \phi_B) \\ i_B(-\sin \theta_B) \end{bmatrix}$$

$$j_i = \begin{bmatrix} j_i^x \\ j_i^y \\ j_i^z \end{bmatrix} = \begin{bmatrix} j_B(\sin \phi_B \sin \theta_B \cos \psi_B - \cos \phi_B \sin \psi_B) \\ j_B(\sin \phi_B \sin \theta_B \sin \psi_B + \cos \phi_B \cos \psi_B) \\ j_B(\sin \phi_B \cos \theta_B) \end{bmatrix}$$

$$k_i = \begin{bmatrix} k_i^x \\ k_i^y \\ k_i^z \end{bmatrix} = \begin{bmatrix} k_B(\cos \phi_B \sin \theta_B \cos \psi_B + \sin \phi_B \sin \psi_B) \\ k_B(\cos \phi_B \sin \theta_B \sin \psi_B - \sin \phi_B \cos \psi_B) \\ k_B(\cos \phi_B \cos \theta_B) \end{bmatrix}$$

## APPENDIX A

where the superscripts  $x$ ,  $y$ , and  $z$  identify the components of the vectors. These nine vector components are the quantities needed to draw the box when the aircraft is on and aligned with the desired path and the box is at an angle to the path. The steps that are needed to account for the aircraft attitudes and displacements from the desired path are now given.

The transformation matrix which converts vectors from inertial coordinates to aircraft body-fixed coordinates is

$$T_A = \begin{bmatrix} \cos \phi_A \cos \theta_A & \sin \phi_A \cos \theta_A & -\sin \theta_A \\ \cos \phi_A \sin \theta_A \sin \phi_A & \sin \phi_A \sin \theta_A \sin \phi_A & \cos \theta_A \sin \phi_A \\ -\sin \phi_A \cos \phi_A & +\cos \phi_A \cos \phi_A & \\ \cos \phi_A \sin \theta_A \cos \phi_A & \sin \phi_A \sin \theta_A \cos \phi_A & \cos \theta_A \cos \phi_A \\ +\sin \phi_A \sin \phi_A & -\cos \phi_A \sin \phi_A & \end{bmatrix}$$

Multiplying the vector difference between the box location and the aircraft location by the transformation matrix  $T_A$  gives the location of the box in aircraft coordinates:

$$\begin{bmatrix} x_{BA} \\ y_{BA} \\ z_{BA} \end{bmatrix} = T_A \begin{bmatrix} x_{iB} - x_{iA} \\ y_{iB} - y_{iA} \\ z_{iB} - z_{iA} \end{bmatrix}$$

Multiplying the box specification vectors by the transformation matrix  $T_A$  gives these vectors in aircraft coordinates

$$i_A = T_A i_i$$

$$j_A = T_A j_i$$

$$k_A = T_A k_i$$

In order to obtain the correct aspect of the display image of the box, the vectors  $i_A$ ,  $j_A$ , and  $k_A$  must be transformed to a visual coordinate system which is aligned with the pilot's line of sight (see fig. A1). The transformation matrix from aircraft coordinates to visual coordinates is

# APPENDIX A

$$T_V = \begin{bmatrix} \frac{x_{BA}}{\sqrt{x_{BA}^2 + y_{BA}^2 + z_{BA}^2}} & \frac{y_{BA}}{\sqrt{x_{BA}^2 + y_{BA}^2 + z_{BA}^2}} & \frac{z_{BA}}{\sqrt{x_{BA}^2 + y_{BA}^2 + z_{BA}^2}} \\ -\frac{x_{BA}}{\sqrt{x_{BA}^2 + z_{BA}^2}} & \frac{y_{BA}}{\sqrt{x_{BA}^2 + y_{BA}^2 + z_{BA}^2}} & \frac{x_{BA}^2 + z_{BA}^2}{\sqrt{x_{BA}^2 + y_{BA}^2 + z_{BA}^2}} & -\frac{z_{BA}}{\sqrt{x_{BA}^2 + z_{BA}^2}} & \frac{y_{BA}}{\sqrt{x_{BA}^2 + y_{BA}^2 + z_{BA}^2}} \\ -\frac{z_{BA}}{\sqrt{x_{BA}^2 + z_{BA}^2}} & 0 & \frac{x_{BA}}{\sqrt{x_{BA}^2 + z_{BA}^2}} \end{bmatrix}$$

Multiplying the vectors  $i_A$ ,  $j_A$ , and  $k_A$  by the matrix  $T_V$  gives the box specification vectors in visual coordinates:

$$i_V = T_V i_A$$

$$j_V = T_V j_A$$

$$k_V = T_V k_A$$

Consider a flat rectangular window in the aircraft cockpit located so that the vector from the pilot's eye to the center of the window is parallel with the aircraft X-axis as shown in figure A2. The distance from the pilot to the window is  $x_W$ . From simple geometric relations, a point in space as seen by the pilot can be projected to a point on the window that is the intersection of the pilot's line of sight with the window. The center of the box, which is located at  $(x_{BA}, y_{BA}, z_{BA})$  in aircraft coordinates, projects to the point

$$C = \left( \frac{x_W}{x_{BA}} y_{BA}, \frac{x_W}{x_{BA}} z_{BA} \right)$$

in window coordinates.

The line of sight to the center of the box is aligned with the visual X-axis. The calculations to project the visible edges of the box to the window are performed relative to the projection of the center of the box with no corrections for the changing distance from the pilot; that is the parallel edges of the box project parallel to and have twice the length of the projections of the vectors  $i_V$ ,  $j_V$ , and  $k_V$ . The projections of the vectors  $i_V$ ,  $j_V$ , and  $k_V$  relative to the center of the box are

$$i_W = \begin{bmatrix} i_W^y \\ i_W^z \end{bmatrix} = \begin{bmatrix} \frac{x_W}{x_{BA}} i_V^y \\ \frac{x_W}{x_{BA}} i_V^z \end{bmatrix}$$

# APPENDIX A

$$j_W = \begin{bmatrix} j_W^y \\ j_W^z \end{bmatrix} = \begin{bmatrix} \frac{x_W}{x_{BA}} j_V^y \\ \frac{x_W}{x_{BA}} j_V^z \end{bmatrix}$$

$$k_W = \begin{bmatrix} k_W^y \\ k_W^z \end{bmatrix} = \begin{bmatrix} \frac{x_W}{x_{BA}} k_V^y \\ \frac{x_W}{x_{BA}} k_V^z \end{bmatrix}$$

Of the six surfaces of the box, only three are visible to the pilot. Therefore, only 9 of the 12 edges of the box are projected onto the window. The vectors  $i_W$ ,  $j_W$ , and  $k_W$  each point to the center of one of the surfaces as shown in figure A3(a). Also, the vectors  $-i_W$ ,  $-j_W$ , and  $-k_W$  each point to the center of one of the remaining surfaces. Since the box is symmetric about each axis, an altered set of specification vectors may be defined as

$$i_p = \begin{cases} i_W & (i_V^x < 0) \\ -i_W & (i_V^x > 0) \end{cases}$$

$$j_p = \begin{cases} j_W & (j_V^x < 0) \\ -j_W & (j_V^x > 0) \end{cases}$$

$$k_p = \begin{cases} k_W & (k_V^x < 0) \\ -k_W & (k_V^x > 0) \end{cases}$$

The altered set of specification vectors  $i_p$ ,  $j_p$ , and  $k_p$  each point to one of the visible sides of the box, as shown in figure A3(b).

The projections of each of the nine visible edges may be defined by specifying an origin and a vector (direction and length) as given in the following table:



# APPENDIX A

Line	Vector	Origin
1	$2i_p$	$C_1 = C - i_p + j_p + k_p$
2	$-2j_p$	
3	$-2k_p$	
4	$-2i_p$	$C_2 = C + i_p - j_p + k_p$
5	$2j_p$	
6	$-2k_p$	
7	$-2i_p$	$C_3 = C + i_p + j_p - k_p$
8	$-2j_p$	
9	$2k_p$	

Although the box may be specified as rectangular, at some orientations the image may be confusing and difficult to interpret. In order to alleviate this problem, a rectangle is drawn on the end face (the face perpendicular to the vector  $i_p$ ), as is shown in figure A4. The lengths of the edges of this rectangle are chosen to be a fraction  $f$  of the lengths of the edges of the end of the box. The rectangle is defined by an origin and a vector for each side as given in the following table:

Line	Vector	Origin
10	$2fj_p$	$C_4 = C + i_p - fj_p + fk_p$
11	$-2fk_p$	
12	$-2fj_p$	$C_5 = C + i_p + fj_p - fk_p$
13	$2fk_p$	

# APPENDIX A

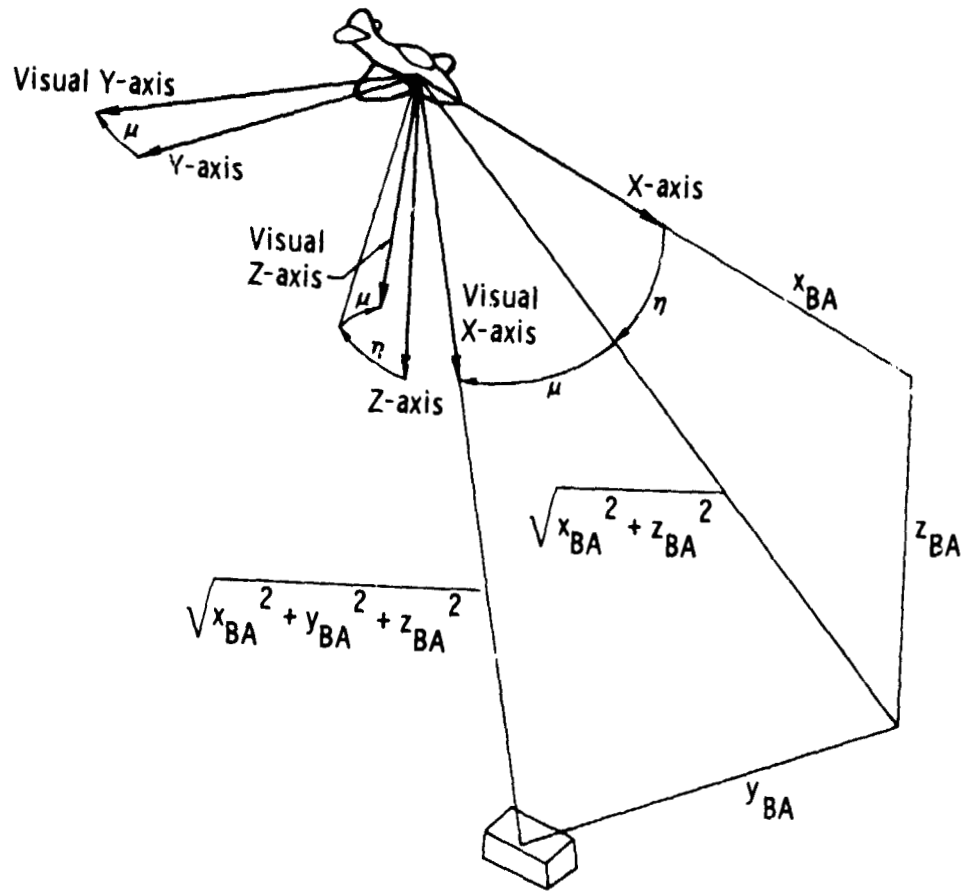


Figure A1.- Visual axis system.

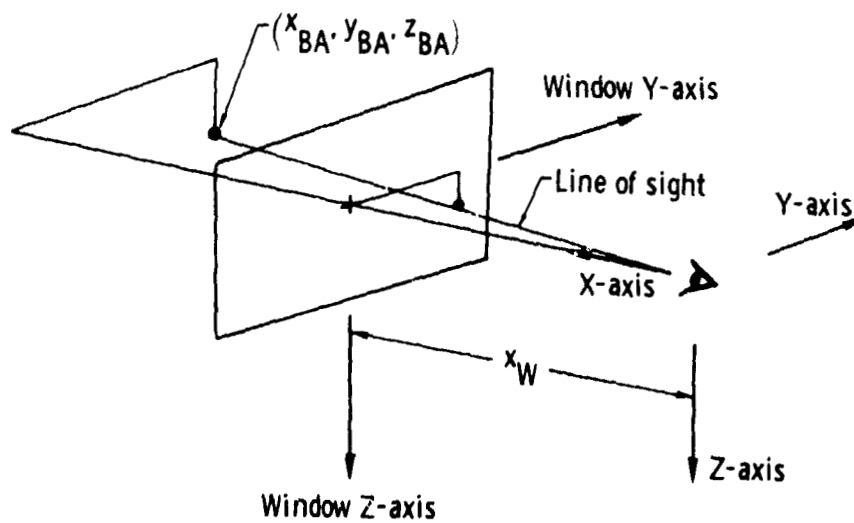
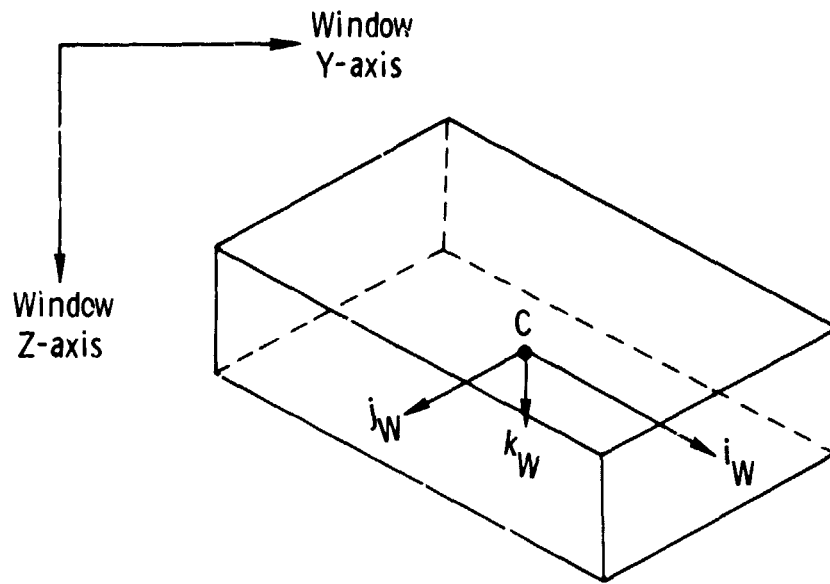
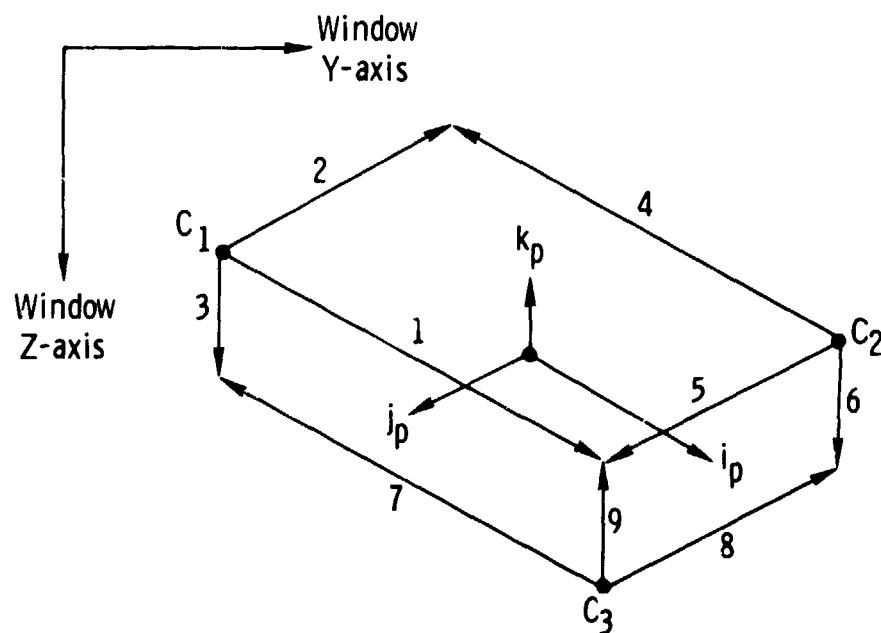


Figure A2.- Window projection system.

# APPENDIX A



(a) Original specification vectors.



(b) Altered specification vectors.

Figure A3.- Box drawing diagram.

# APPENDIX A

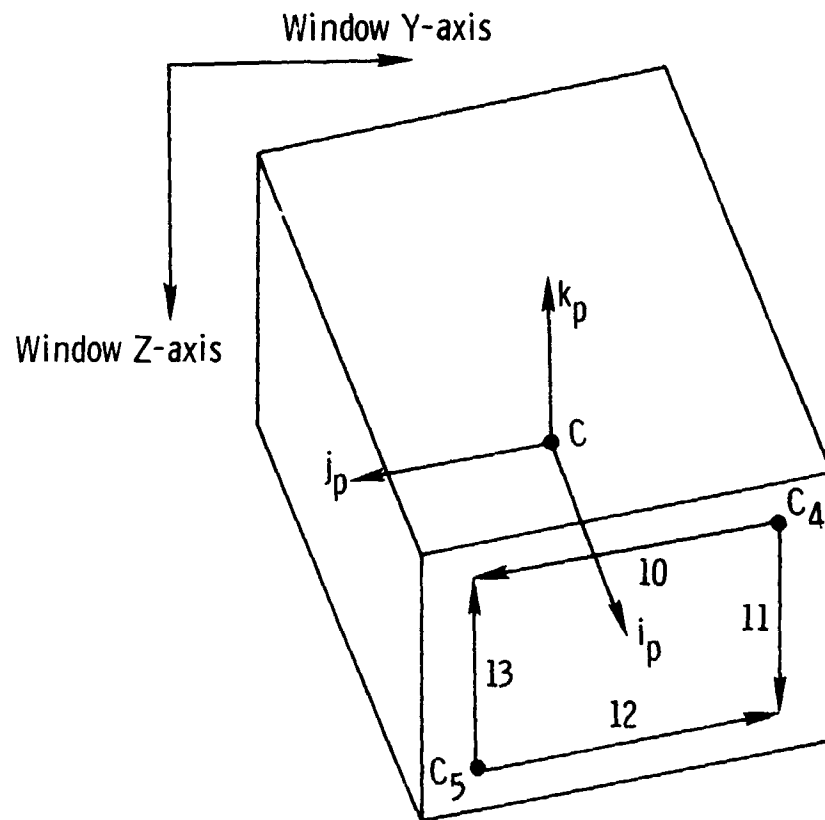


Figure A4.- End-face figure.

## APPENDIX B

### PILOT ANSWERS TO QUESTIONNAIRE

This appendix presents the responses of the subject pilot to several questions concerning the display system used in this study. A questionnaire was given to each pilot after he had completed his simulated flights. Each question is presented below followed by the responses of all nine subject pilots.

1. Did you have enough time to become stabilized on the glide-slope localizer while using the box display?

Subject 4: Yes.

Subject 5: I think so, but I seemed too busy tracking the heading in order to really evaluate this.

Subject 8: Yes.

Subject 3: Yes, I had enough time to become stabilized (i.e., a steady state oscillation).

Subject 9: Yes.

Subject 1: Yes, for most cases. On one approach I got above the glide-slope and captured it [at] only about 300 feet altitude. Box not very precise in glide slope and sometimes seemed to disagree with HSI glide-slope indicator. HSI glide slope had to be included in scan.

Subject 7: Yes.

Subject 6: Yes, although I overshot the localizer every time. And I felt I needed more altitude cues.

Subject 2: Yes. However many runs were essentially for a zero cross-wind condition and I don't know what control technique is required or what my performance would be in a cross-wind condition. For this task I ignored secondary instruments which I would need for cross-wind conditions and hence my work load was less than normal.

2. Did you feel confident about your ability to touchdown when using the box display?

Subject 4: I only used the box display to the decision height. The touchdown and flare were visual. I felt confident to decision height.

Subject 5: Not initially, but after the third approach I gained some confidence and ability.

Subject 8: Yes.

Subject 3: No. This may have come with more practice. I did not go from instrument flight to visual flight enough times to relate in my mind how far off course [I was] on the box display [to] how far off course [I was] in "real world."

## APPENDIX B

Subject 9: I had good confidence to breakout. Used outside scene for reference during flare and touchdown.

Subject 1: In later stages of approach, I felt more confident about lateral situation but less confident with vertical situation with box alone. Had to include HSI glide slope in scan.

Subject 7: Yes.

Subject 6: I didn't use the box for touchdown.

Subject 2: I felt good about my location relative to the runway at breakout, but the landing scene and aural cues do not identify the occurrence of touchdown.

### 3. Please make specific comments on the box display. What are its best features? Its worst?

Subject 4: Best features:

- Good 3-D picture of current position relative to way point
- Seemed to make coordinated maneuvers (such as climbing turns) easier than using HSI and altimeter to get back on profile and path simultaneously
- Reduced scanning requirements
- Was easier to understand and to fly

Worst features:

- Determining relative position was a strain at long range due to small box size
- Exact paths to intercept inbound course to next box are not shown and therefore will be variable between runs and pilots. Wouldn't work well in the real world where obstruction clearance, etc., get involved in determining airspace requirements
- Takes slightly longer [I think] to reacquire your relative position to the box after looking away, compared to getting the info from an HSI. This would be more of a problem if there were landing checklists and other distractions in the cockpit.

Subject 5: Bigger lettering and a better quality CRT is needed, i.e., blurring of boxes caused much confusion. The worst feature is not so much a problem with [the] boxes themselves as it is understanding what is really meant by the stationary/moving boxes. More education is needed before flying this simulation. No pilot in his right mind would even attempt an approach using this setup without first getting checked out with safety pilot. The best feature (after considerable thought) is the fact that the task could be performed without aircraft attitude info (pitch, roll, heading, altitude). This info is very desirable however. Because of prior basic training, every pilot wants to know his aircraft attitude, which in reality, may be unnecessary if one can do the task safely. The boxes really provide the altitude guidance needed with little reference to the altimeter. Nice!

## APPENDIX B

### Subject 8: Best features:

- It gives you easy-to-follow guidance to the next way point, including altitude information (assuming you are within  $\pm 45^\circ$  of the proper direction)
- The 3-D perspective gives you some idea of your desired approach angle to the way point, but is lacking in some respects (see discussion below)
- The second box gives pretty good cues to prepare you for the direction to turn and whether to climb or descend at the next way point
- The holding display is very good, but may have some practical implementation problems.

### Worst features:

- It's too small! You need a bigger CRT to get the proper size and resolution for efficient pilot use. I found myself leaning forward to see the box; it's hard on the eyes.
- Resolution is sometimes not good enough to determine box orientation.
- Cluttering is a problem around the center of the screen whenever the box is fairly small. The box, horizon line, and (+) symbol all run together.
- Although the box provides some information regarding your position relative to the desired track, drift angle information (wind effects) are not shown as well as conventional displays using CDI or HSI.
- If you don't have the box in sight, there are no cues to turn in the proper direction to find it. This can be a serious problem.
- The absence of roll and pitch angle indices means it is unsatisfactory for general purpose use.
- Skewing of the lines making up the box sometimes occurs, making assessment of the box orientation difficult.

Subject 3: Best feature: Small amount of instruction allows pilot to use display for successful IFR approach

Worst feature: Display needs a way to inform the pilot of off-course limits during the ILS approach (such as needle going off scale on glide-slope indicator).

Subject 9: Best feature: Good command indicator of glide-slope/localizer.

Worst feature: Display flicker was very bad. Display too small. Aircraft longitudinal axis cross got lost in clutter.

Subject 1: Lines in drawing too small; same for printed messages. Could not tell with the box when I was within  $10^\circ$  of course line or  $2.5^\circ$  of localizer to begin descent. Also descents after fixes are not supposed to commence until the fix is past. The switching system used would have permitted the pilot to begin the descent 1 or 2 or more miles prior to the fix depending on when the switch was made. Should have distance-to-fix shown below the box. There is a poor feature of the display in that guidance information can be totally

## APPENDIX B

lost by changing heading more than 45°. This would be especially bad in a situation where a wind correction angle of 30° or so was required.

Provided much better indication of orientation to ILS while on downwind/base than HSI.

Subject 7: There is a definite learning curve in using the box.

Subject 6: The boxes seem to provide good lateral cues unless the intercept angle is large. I don't feel comfortable with respect to the desired altitude I should be maintaining or approaching. In a real airplane I would feel nervous about the proximity of the ground on an ILS approach. Small changes in perspective translate to relatively large altitude variations. I had no idea what level of altitude error would require the execution of a missed approach while on final approach, for example.

Subject 2: I believe the work load might be less in a cross-wind instrument landing. Also it circumvents the variable sensitivity problem associated with standard ILS.

As indicated in answer 1, the utility of the box in a cross-wind landing needs to be evaluated before its merits can be established. The display should have graduated scales for bank angle and pitch altitude. As control variables, the pilot needs numerical measures of these states for precise trajectory control and safety. The box display seems comparable to flight director instruments and should be evaluated relative to such systems.

Some type of performance tolerances are needed on the display to indicate to the pilot when a missed approach should be executed. What I have in mind are glide-slope tolerances.

4. Please compare using box display with the HSI for the type of close-in approach performed in the test.

Subject 4: I feel like the HSI allowed more precise tracking than the box display (the data will tell) but the box was easier to fly. Again, I feel like getting back on path and profile simultaneously is easier with the box, but judging when you are just a little off is more difficult than with HSI with glide slope. Cross winds seemed to be about equally difficult with both techniques.

Subject 5: I can't really answer this question fairly as I haven't flown an HSI on an instrument approach in quite a while. Aircraft I've flown recently have separate heading and VOR repeaters.

Subject 8: Given all the adverse features mentioned above, and assuming they could be corrected, perhaps some comparison can be made. However, a more appropriate comparison should even then probably be drawn between the box and a conventional flight director system (you didn't have the FD). I say this because your box display assumes some fairly sophisticated avionics and should therefore be expected to compete with fairly sophisticated avionics (such as an FD system). With all that in mind, I feel that a good RNAV flight director system would probably result in as good performance as you will get with the box system. However, if some of the deficiencies of the box



## APPENDIX B

system are corrected, I really do like the feeling of space orientation that it gives you and which is missing from a flight director system. That is, you feel like you know where you are relative to where you are going and that is very satisfying.

Subject 3: I have not had enough experience with HSI to make comparisons.

Subject 9: Box is good command display. HSI provides better situation information.

Subject 1: I felt that the box display provided a good picture of the situation and would reduce overcontrolling and PIO's but was not as sensitive (accurate?) as the HSI. Could easily be dangerously below the glide slope at decision height and not realize it from the box.

Subject 7: The box is better for gross errors. The HSI is better for very small errors.

Subject 6: Didn't fly the HSI.

Subject 2: I am not able to make such a comparison without additional familiarization runs with the HSI. An HSI is not a standard instrument for single-engine, single owner GA aircraft.

5. Do you feel that a box display would increase utilization and safety of the aircraft you fly?

Subject 4: Increase utilization? No. I don't think the box display would allow me to fly in conditions I cannot currently fly with HSI. Remember, for most general aviation pilots a CDI is still standard, with HSI being a luxury, and even CDI's get you to 200 feet decision height. Increase safety? Not sure. The box seemed easier to fly, but I'm not sure how my tracking accuracy was affected. I think more time is needed to get further up on the learning curve with the box before I could make a judgment.

Don't give up - it's not a bad idea. I think most of the problems would be in getting something like the box display implemented. It would require a fairly sophisticated onboard computer and display and extensive tests to assure FTE is within currently allowed bounds.

Subject 5: I think it would possibly increase safety, but as far as utilization is concerned I'm not so sure. Utilization of GA aircraft depends on things such as anti-icing equipment and aircraft reliability. I know personally that there have been many times when I chose not to fly due to low icing levels. This is commonly referred to as being "chicken" for longevity reasons. The overall simulation is most realistic and I thank you for your time.

Subject 8: Not with all the limitations it presently has. However, it is a good concept and should be developed further. With further development and testing it might well be shown to increase safety of flight, especially in a single pilot IFR environment.

APPENDIX B

Subject 3: Yes, I think the box display could increase the safety of aircraft I fly.

Subject 9: No.

Subject 1: No, I would feel as comfortable flying to a 200-foot decision height with the HSI as with the box.

Subject 7: No. However I believe with experience flying the box, I would feel more comfortable with it.

Subject 6: Not as simulated because of reasons stated under [question] 3.

Subject 2: I don't see that the box would influence utilization (cost would probably preclude its widespread use), but in application it might increase safety. However, a flight director system would probably provide equivalent performance and benefits.

#### REFERENCES

1. Larson, George C.: Fly on Instruments. Doubleday & Co., Inc., 1980.
2. Forsyth, Donna L.; and Shaughnessy, John D.: Single Pilot IFR Operating Problems Determined From Accident Data Analysis. NASA TM-78773, 1978.
3. Adams, James J.; and Lallman, Frederick J.: Description and Preliminary Studies of a Computer Drawn Instrument Landing Approach Display. NASA TM-78771, 1978.
4. Barnes, A. G.: A New Form of Director Display - The 'Lead Aircraft' Concept. Rep. No. Ae.206, British Aircraft Corp. (Bristol, England), Mar. 1964.
5. Adams, James J.: Simulator Study of Conventional General Aviation Instrument Displays in Path-Following Tasks With Emphasis on Pilot-Induced Oscillations. NASA TP-1776, 1980.
6. Rollins, John D.: Description and Performance of the Langley Visual Landing Display System. NASA TM-78742, 1978.
7. Jacobson, Ira D.; and Joshi, Dinesh S.: Effects of Simulated Turbulence on Aircraft Handling Qualities. Rep. No. UVA/528066/ESS77/106 (Grant No. NGR 47-005-208(4)), Dep. Eng. Sci. & Syst., Univ. of Virginia, Mar. 1977. (Available as NASA CR-152621.)
8. Sarma, Garimella R.; and Adams, James J.: Simulator Evaluation of Separation of Display Parameters in Path-Following Tasks. NASA TP-1915, 1981.

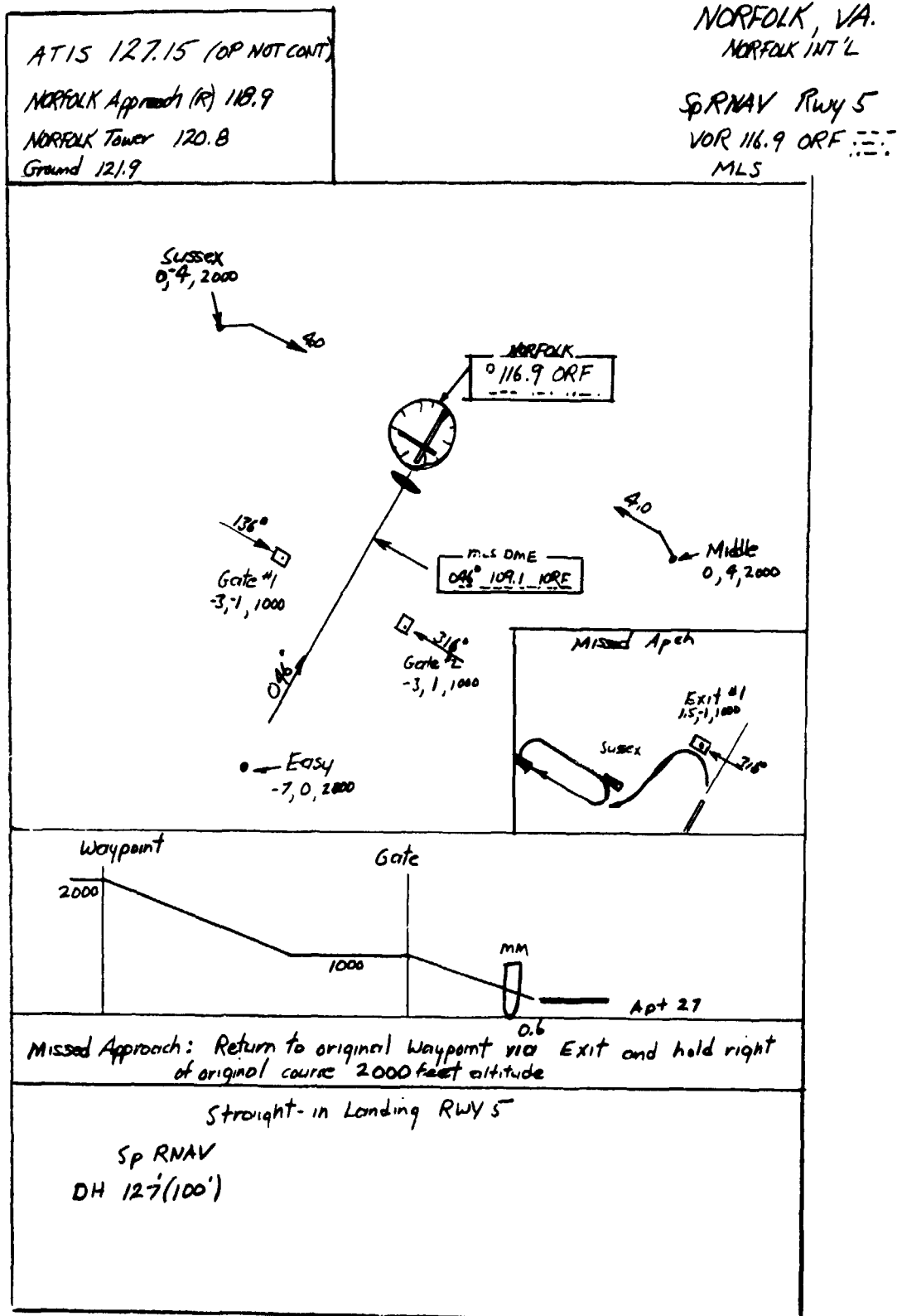


Figure 1.- Approach chart used in study.

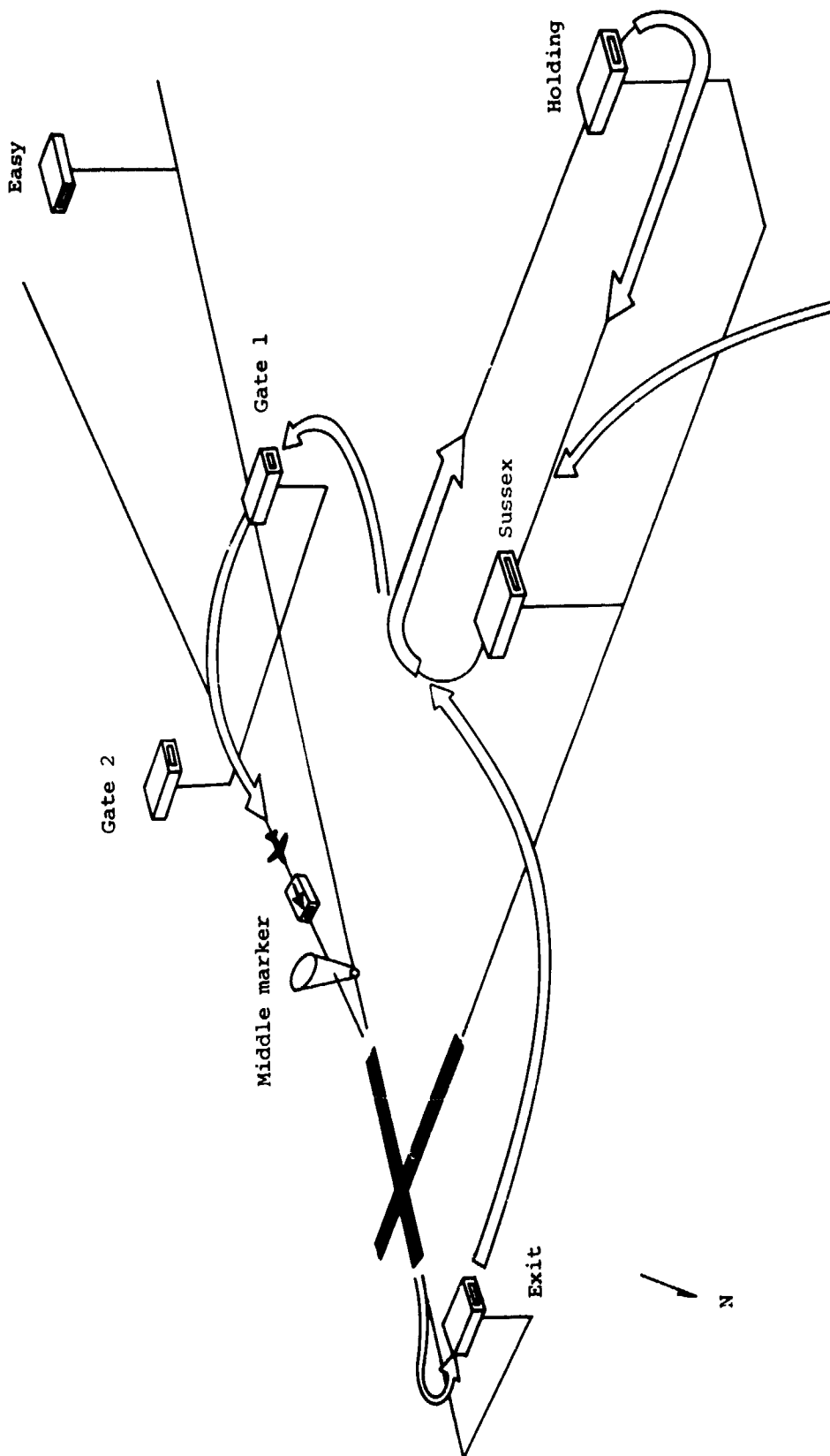


Figure 2.- Flight task.

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Figure 3.- Leaving Sussex and turning to Gate 1. L-81-3386  
(Aircraft is 60 m above desired path.)



Figure 4.- Entering final approach. L-81-3385

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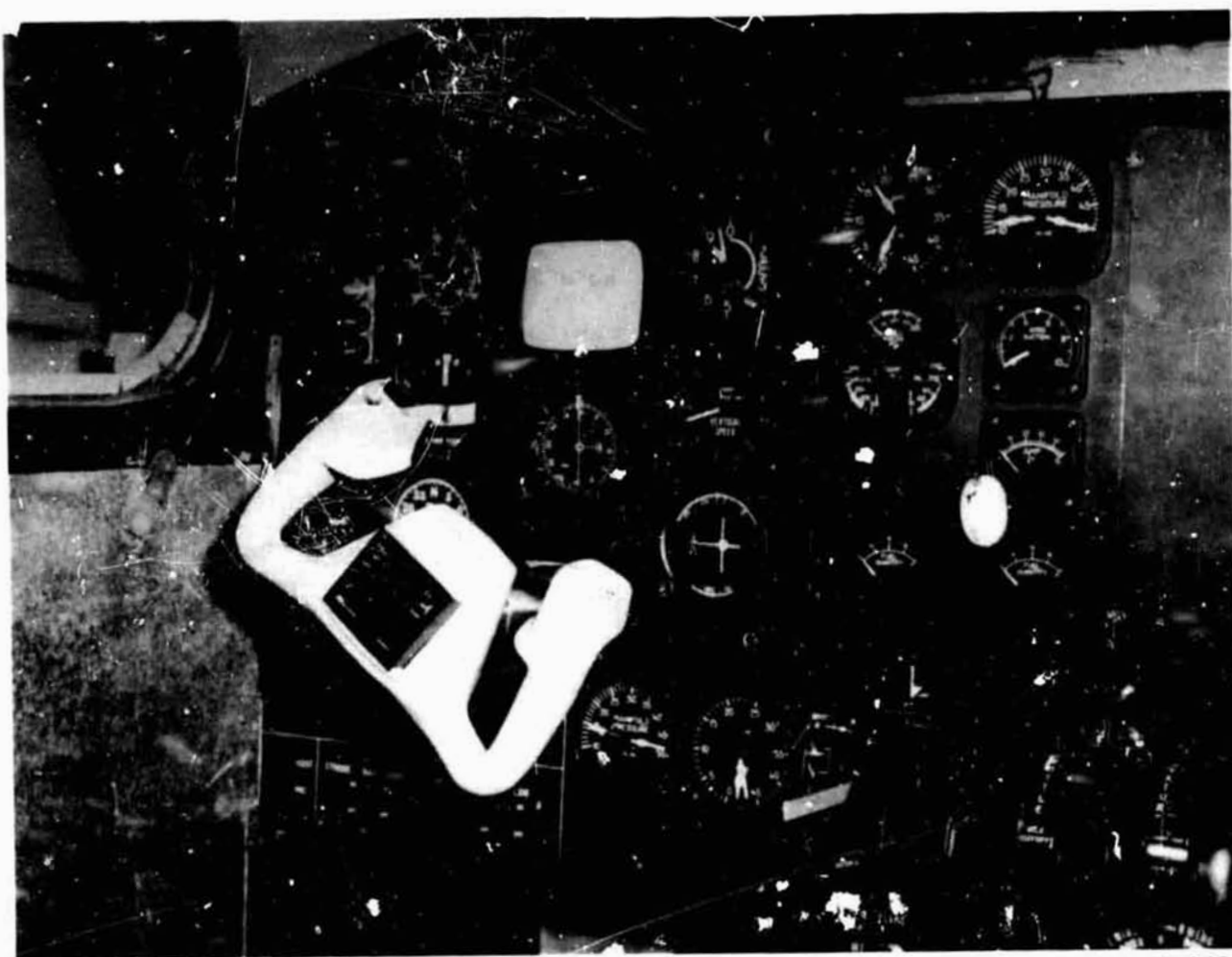
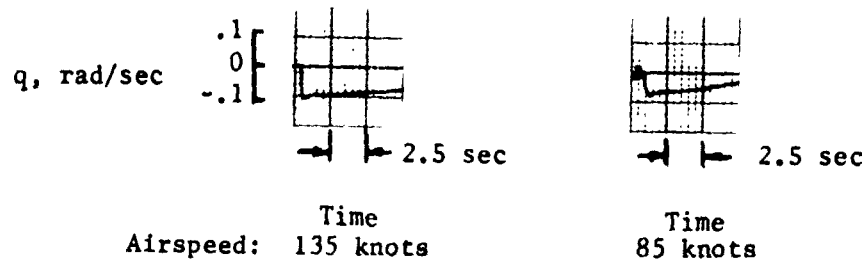
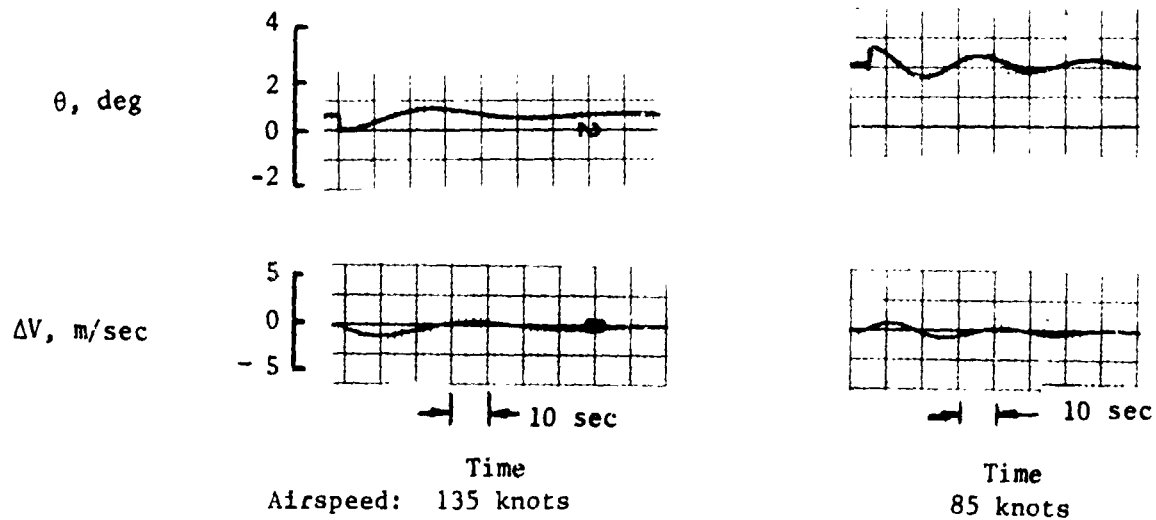


Figure 5.- Instrument panel of simulator.

L-80-10,913



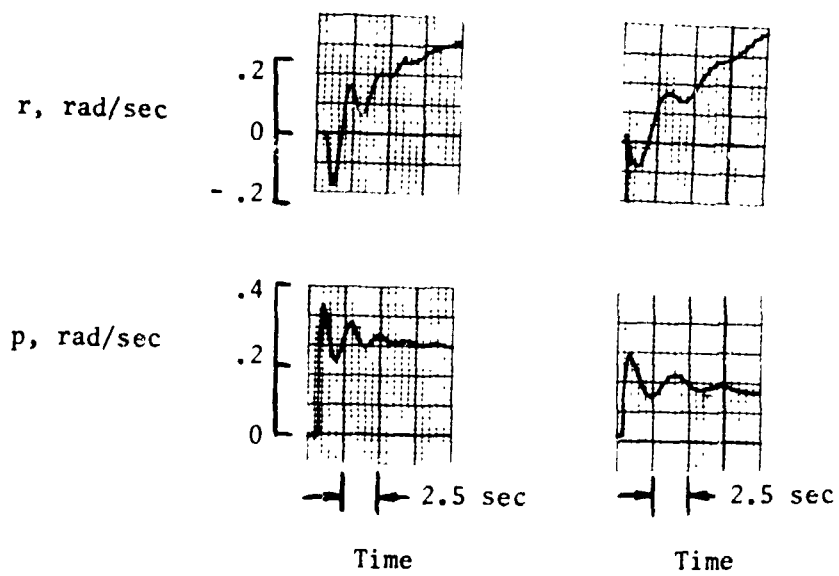
(a) Short-period longitudinal response to a 0.02-rad elevator step input.



(b) Phugoid response to an initial out-of-trim  $\alpha$ .

Figure 6.- Longitudinal response of aircraft.

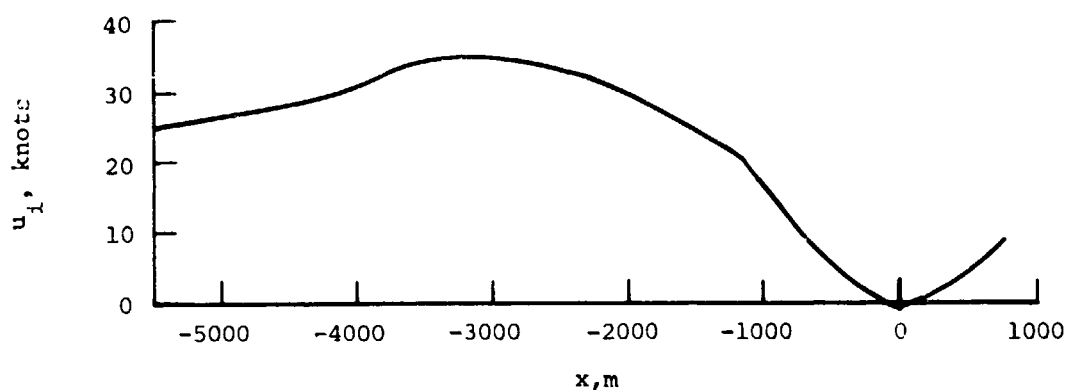




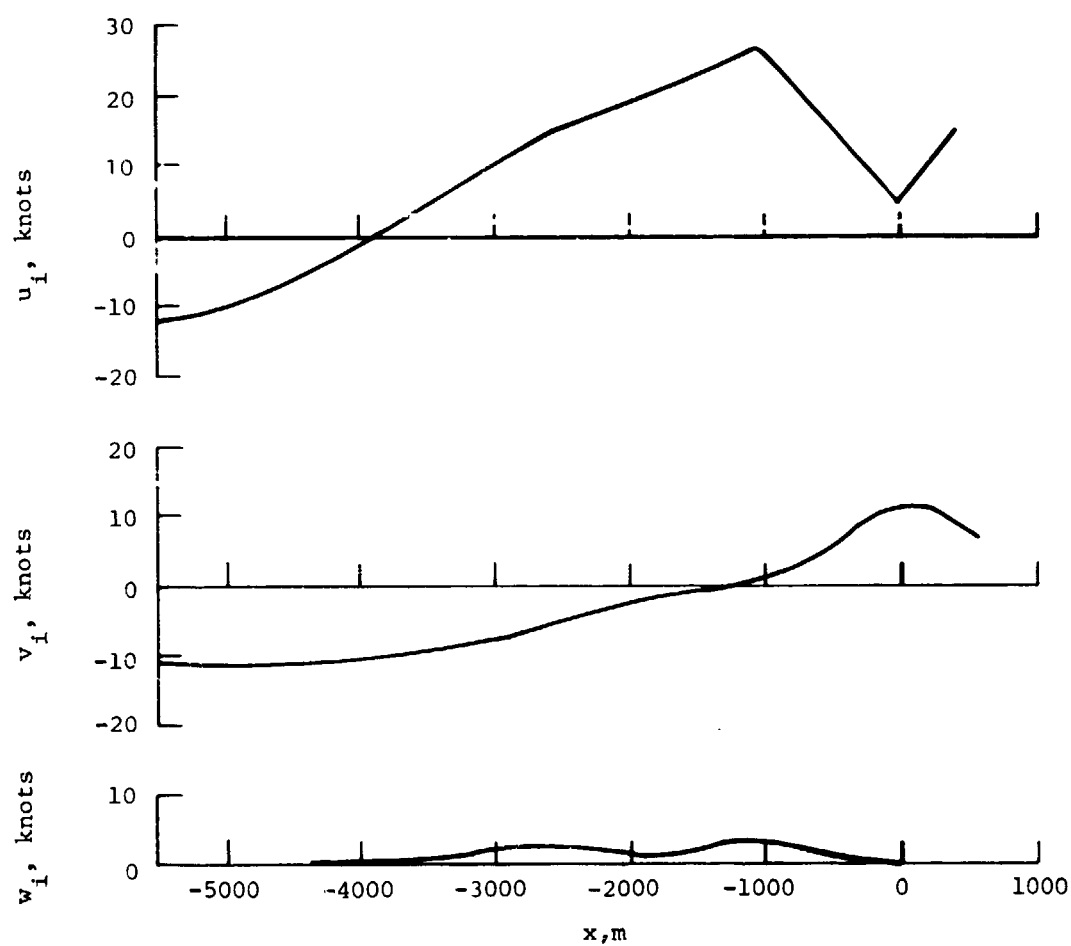
(a) Airspeed, 135 knots.

(b) Airspeed, 85 knots.

Figure 7.- Lateral response to a 0.068-rad aileron step.



(a) Nighttime stable wind condition.  $v_i = w_i = 0$ . Combined with 0.61 m/sec random gust.



(b) Moderate thunderstorm wind condition. Combined with 1.21 m/sec random gust.

Figure 8.- Wind profiles along final approach.

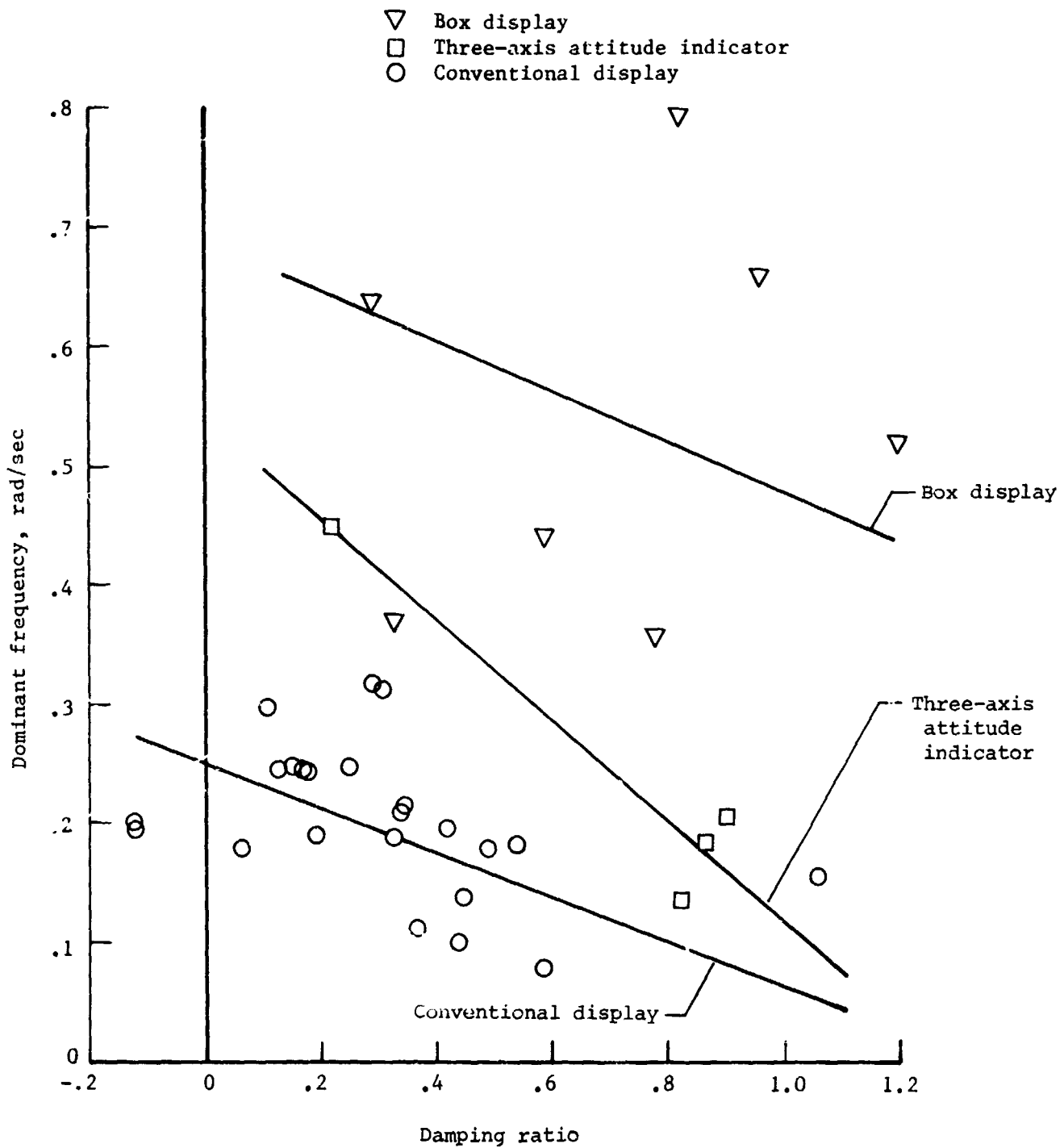


Figure 9.- Dominant frequency and damping ratio of pilot-aircraft-display system.

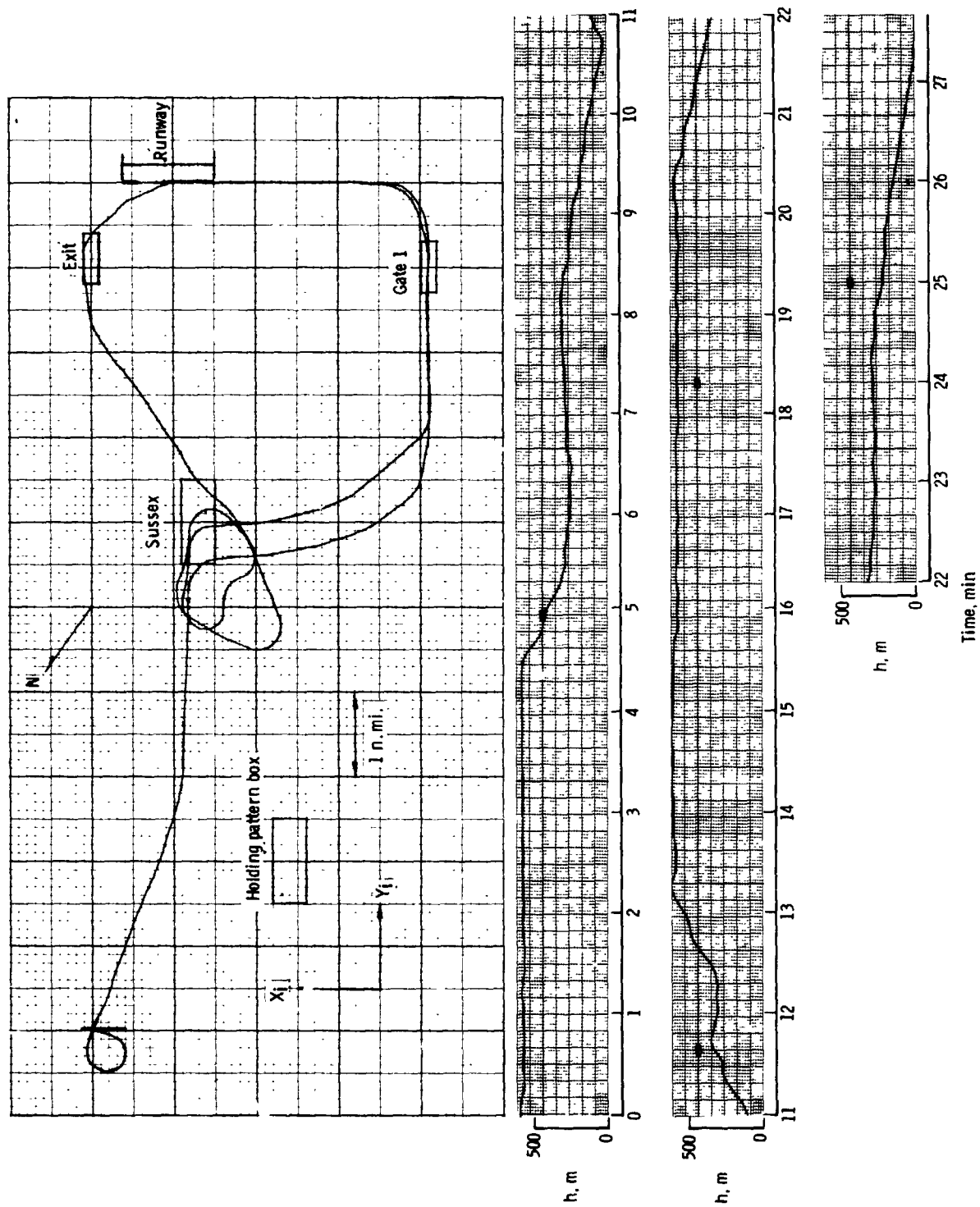


Figure 10.- Ground plot and altitude profile of first flight by subject 4.

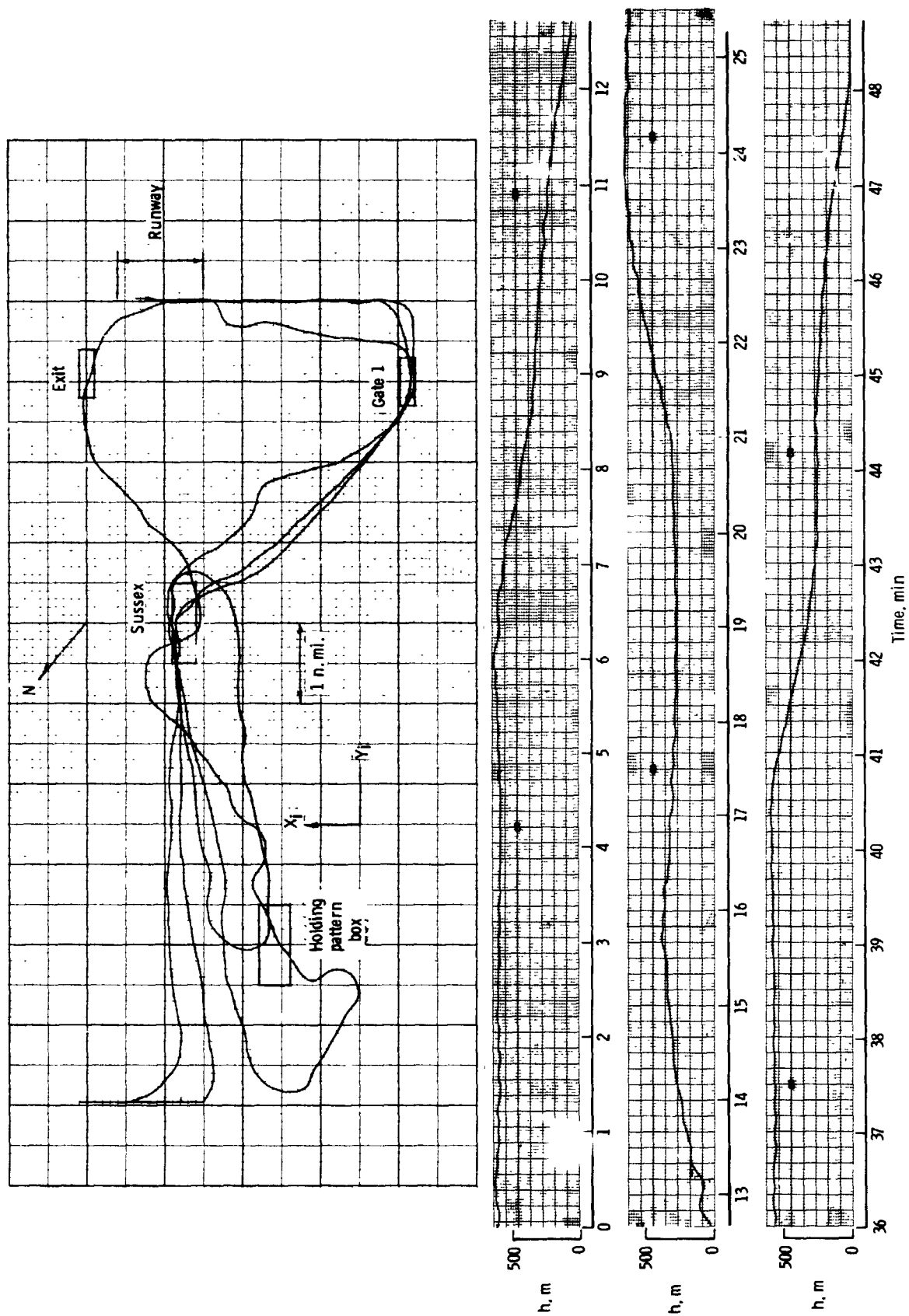


Figure 11.- Ground plot and altitude profile of first flight by subject 5.

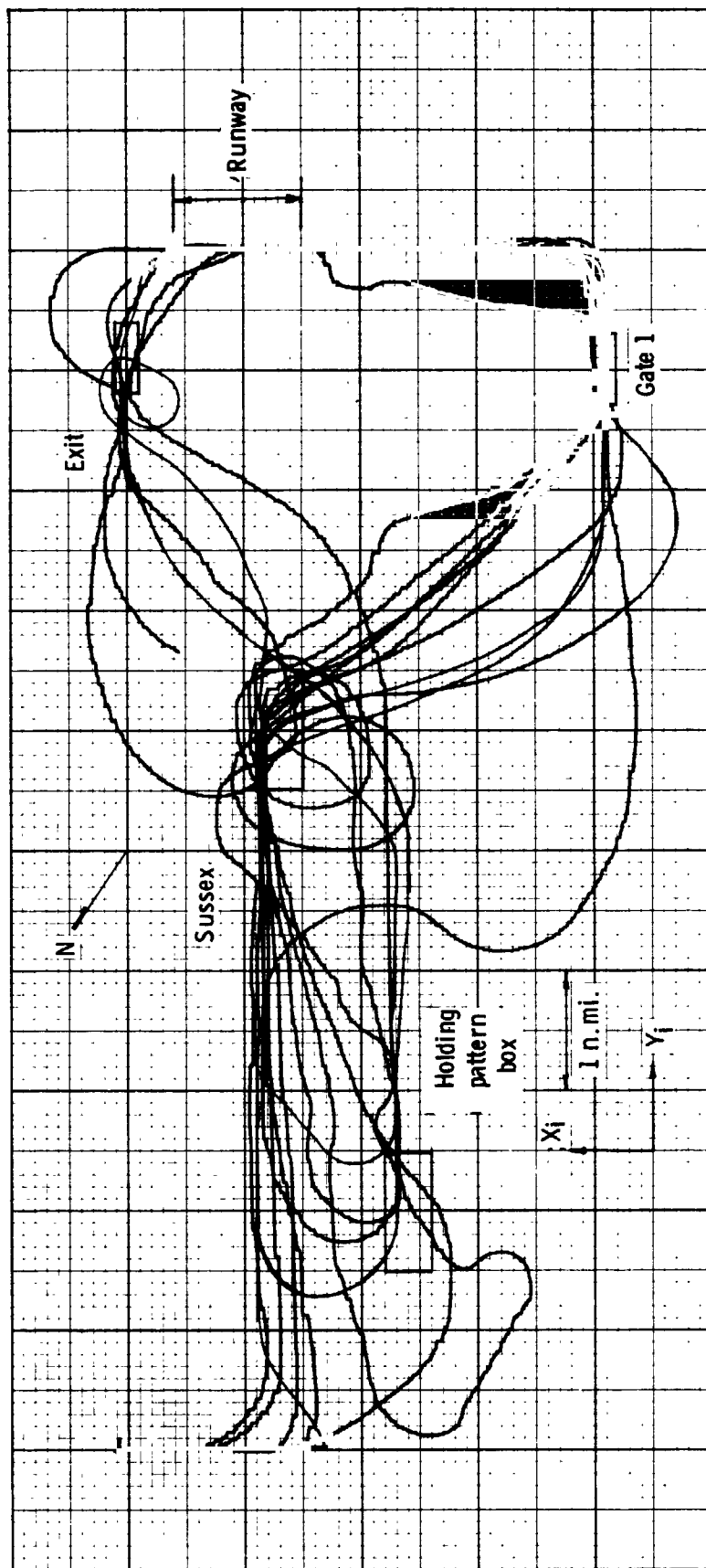


Figure 12.- Ground plots of first flights by subjects 5, 6, 7, 8, and 9.

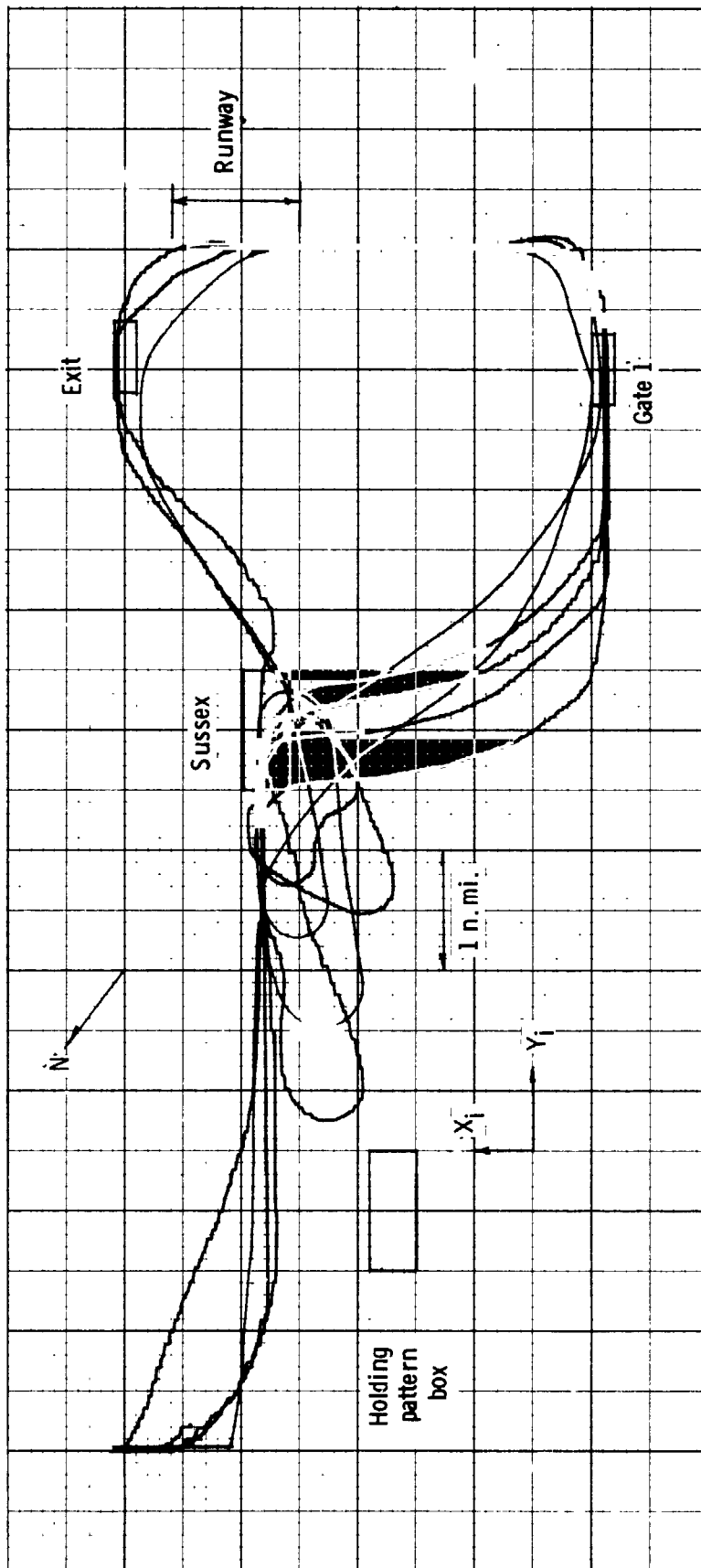


Figure 13.- Ground plots of first flights by subjects 2, 3, and 4.

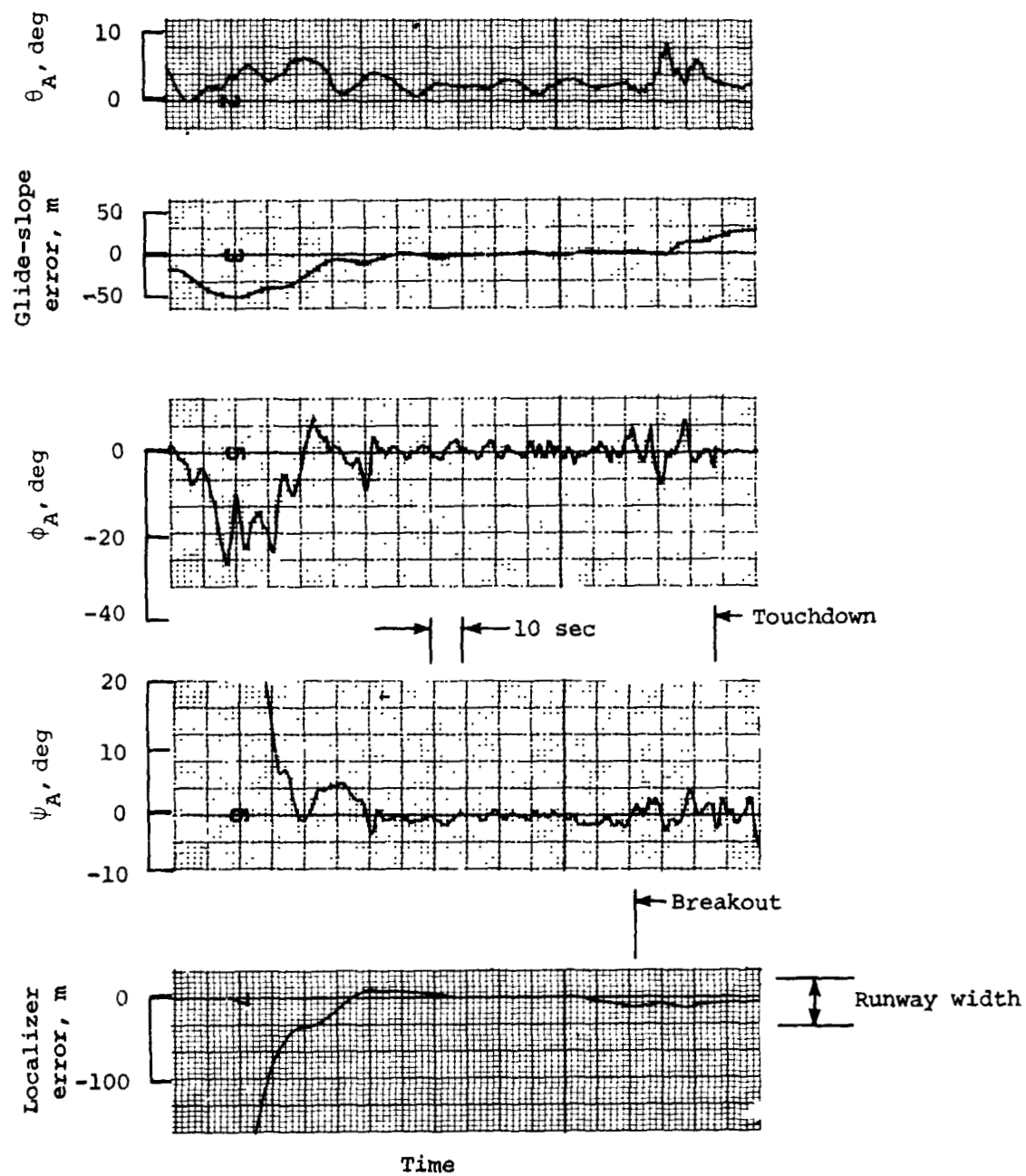


Figure 14.- Time histories of final approach during first flight by subject 4.



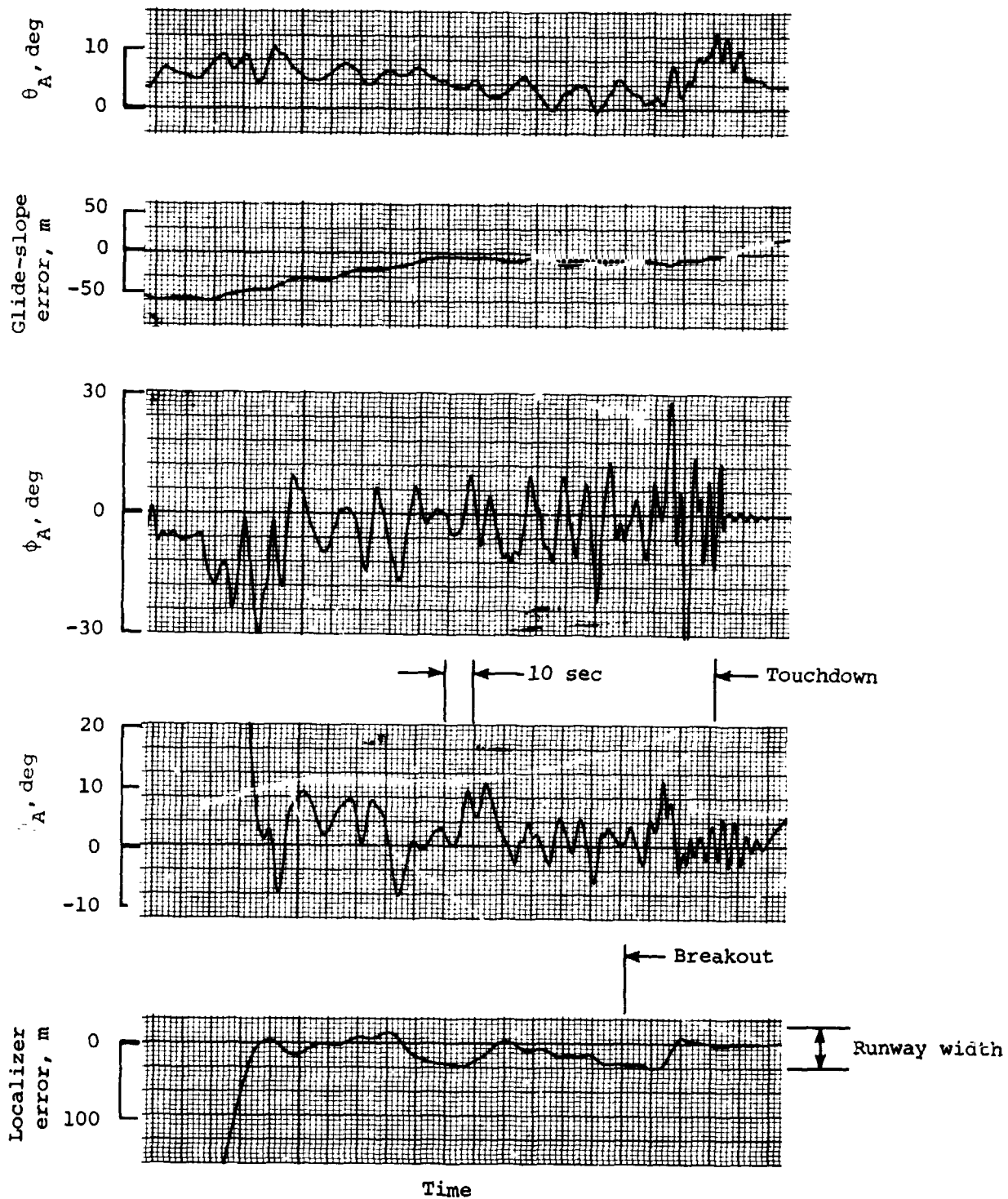


Figure 15.- Time histories of final approach during first flight by subject 5.

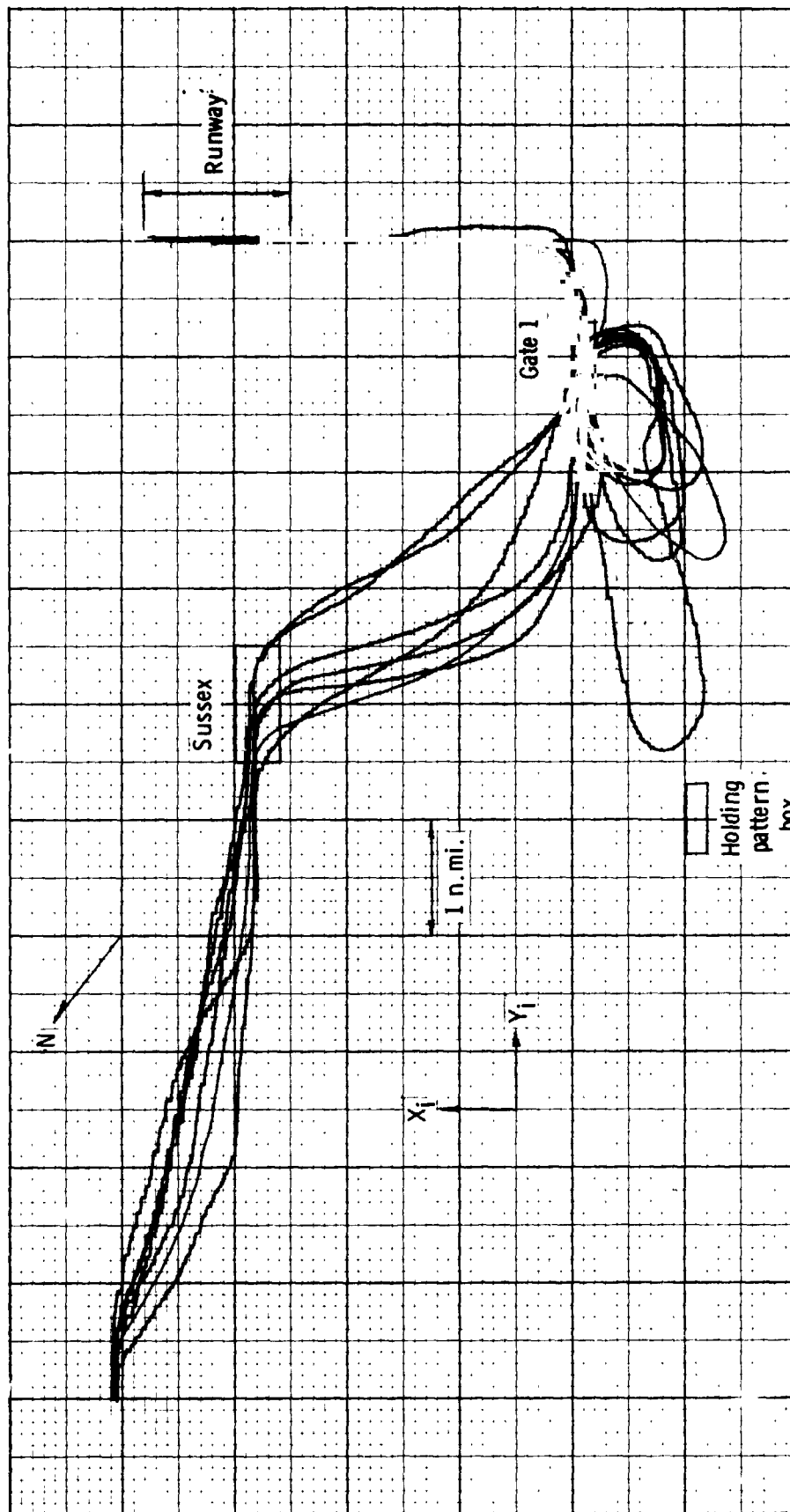


Figure 16.- Ground plots of second flights by subjects 2, 3, 4, 5, 7, 8, and 9.

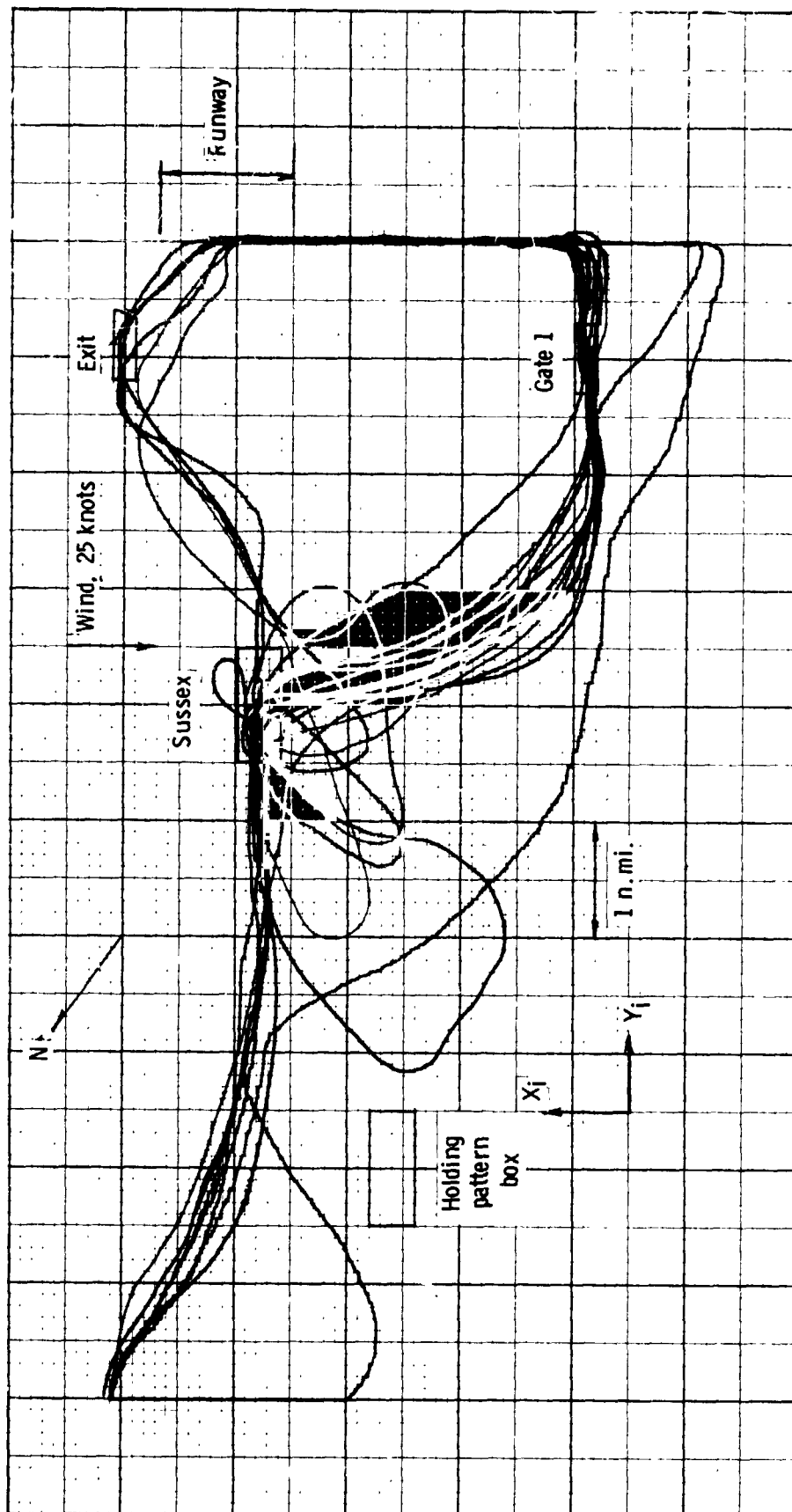


Figure 17.- Ground plots of third flights by all subjects. Nighttime stable wind condition.

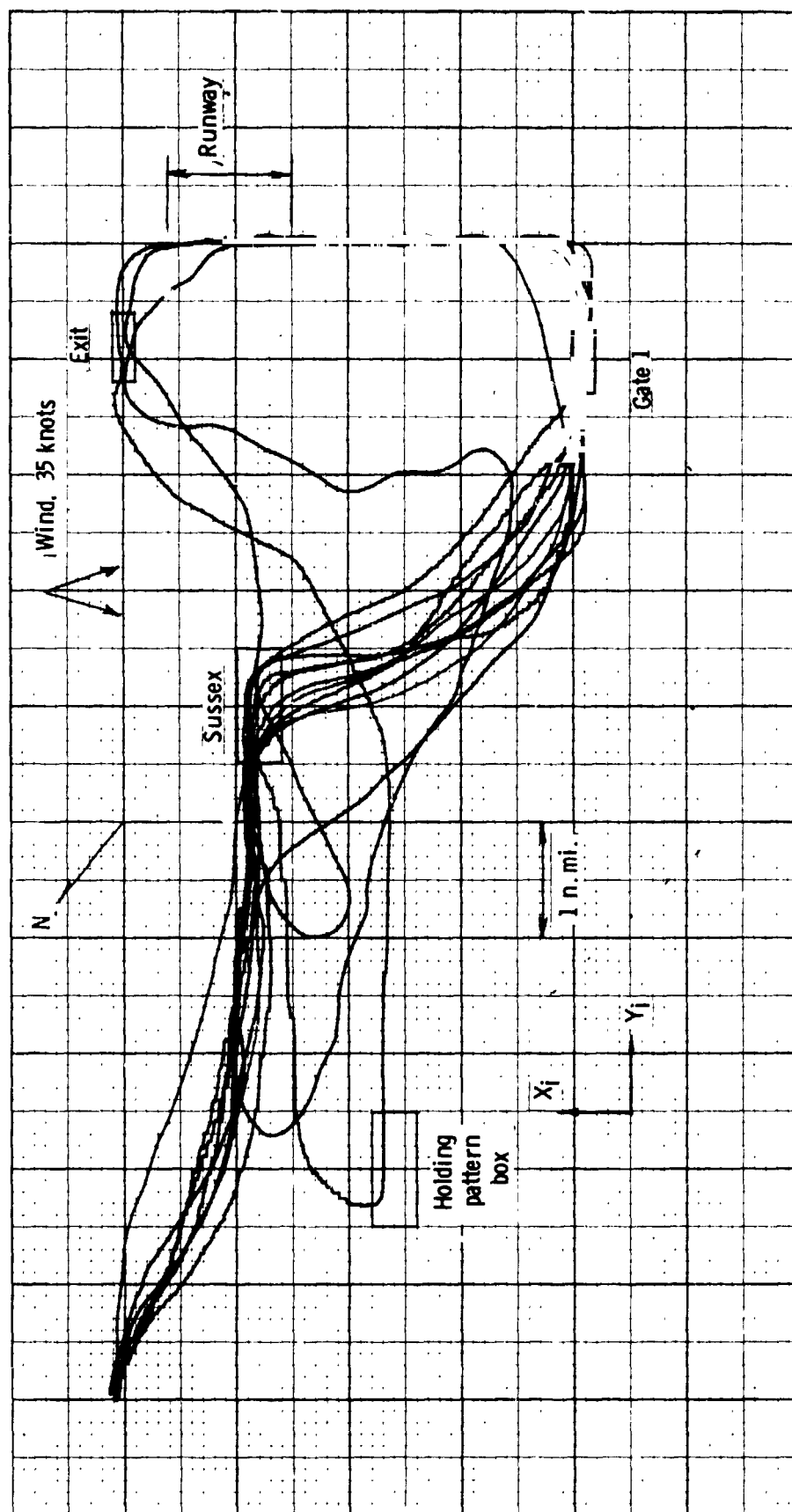


Figure 18.- Ground plots of fourth flights by all subjects. Moderate thunderstorm wind condition.

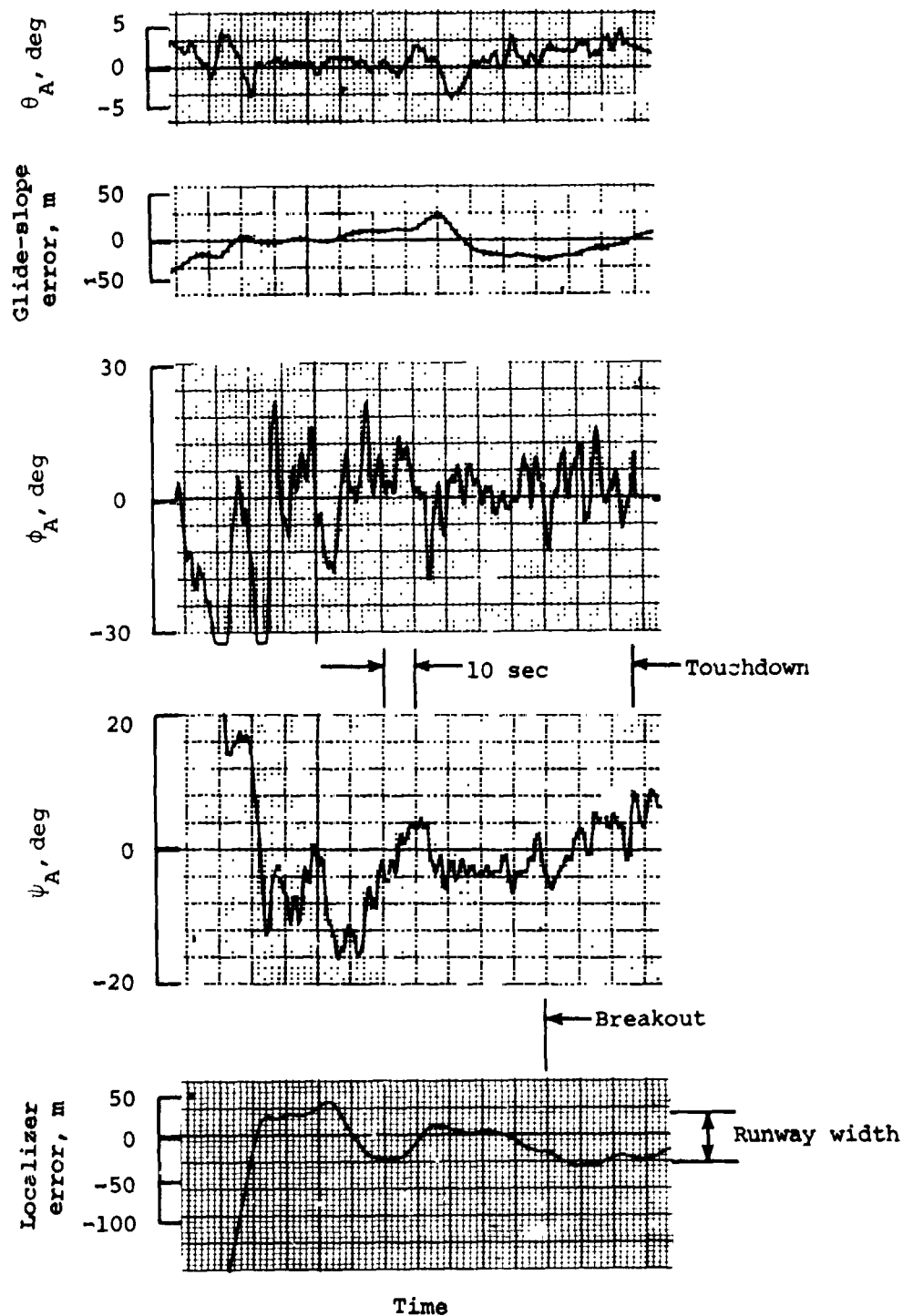


Figure 19.- Time histories of final approach during fourth flight by subject 4 with moderate thunderstorm wind condition.

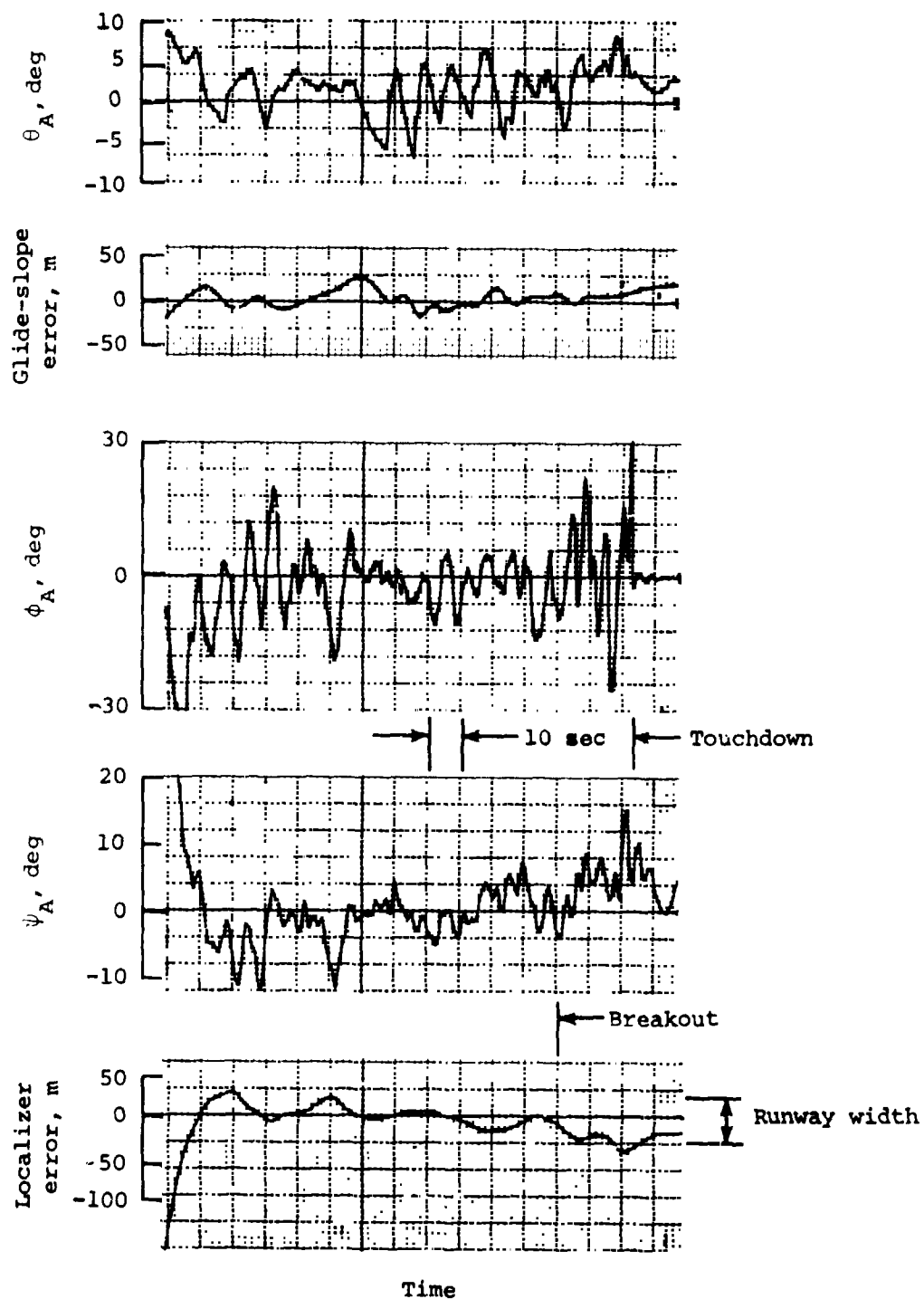


Figure 20.- Time histories of final approach during fourth flight by subject 5 with moderate thunderstorm wind condition.

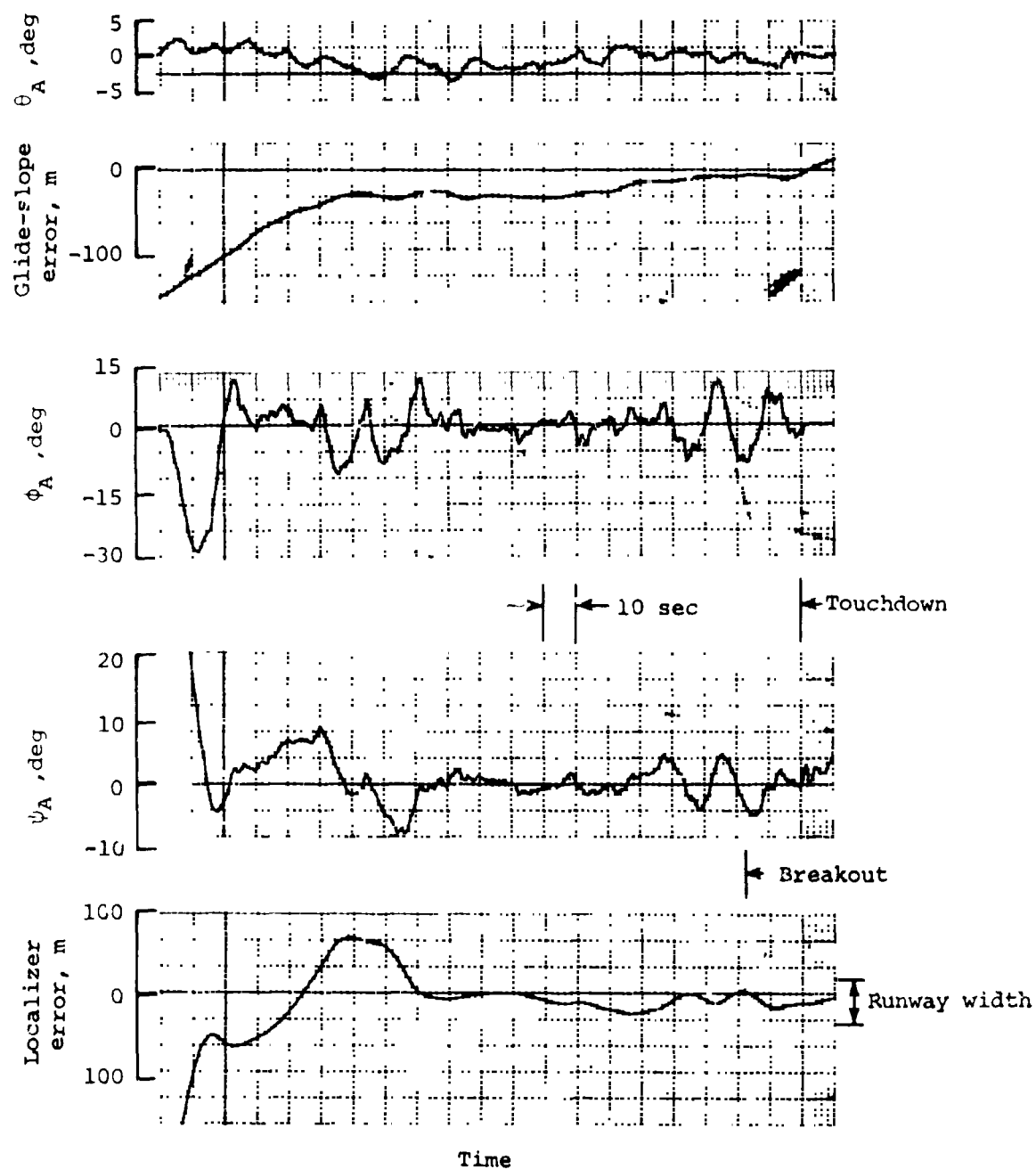


Figure 21.- Time histories of final approach using conventional HSI by subject 8. No winds.

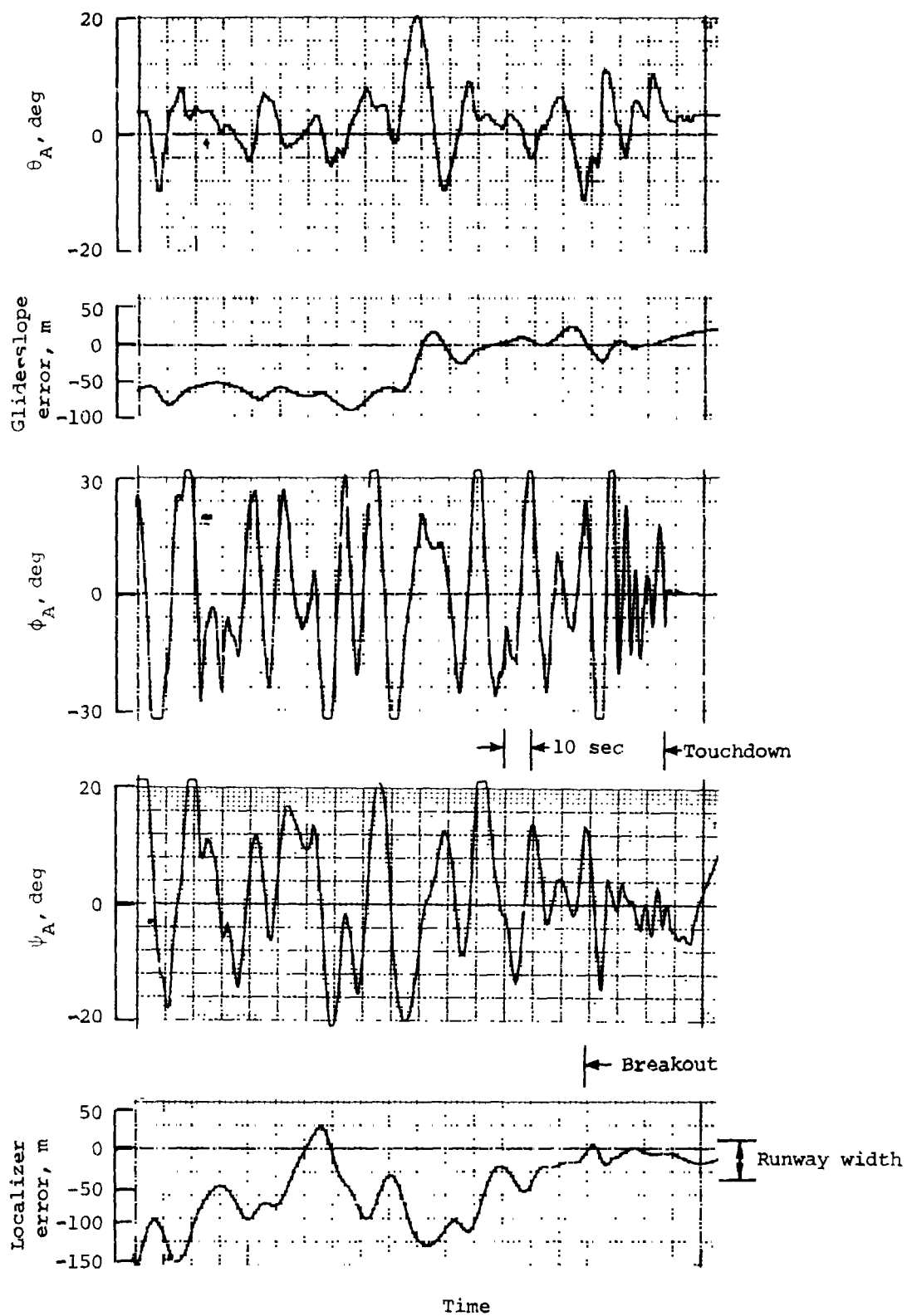


Figure 22.- Time histories of final approach using conventional HSI by subject 5. No winds.



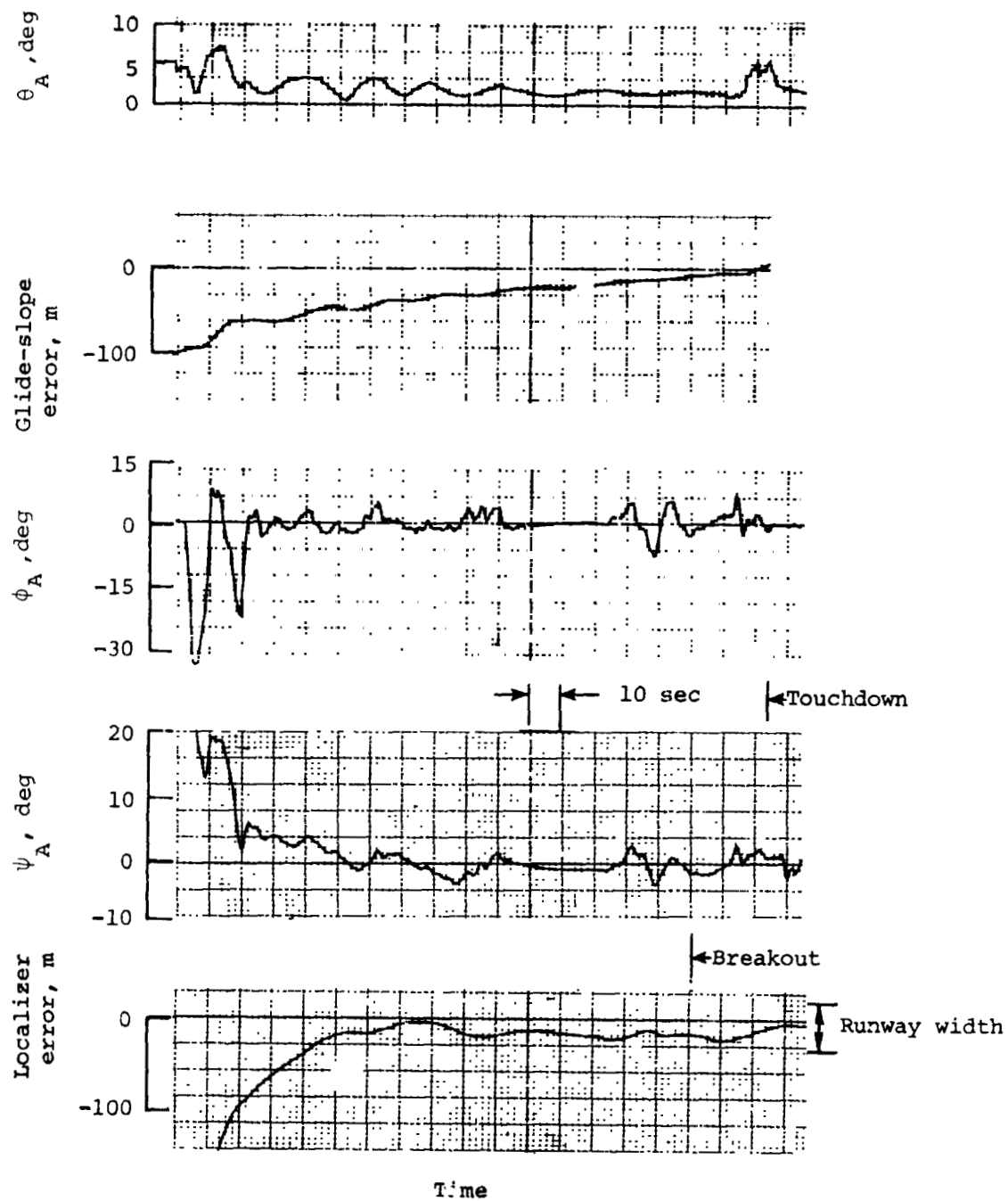


Figure 23.- Time histories of final approach using conventional HSI by subject 4. No winds.

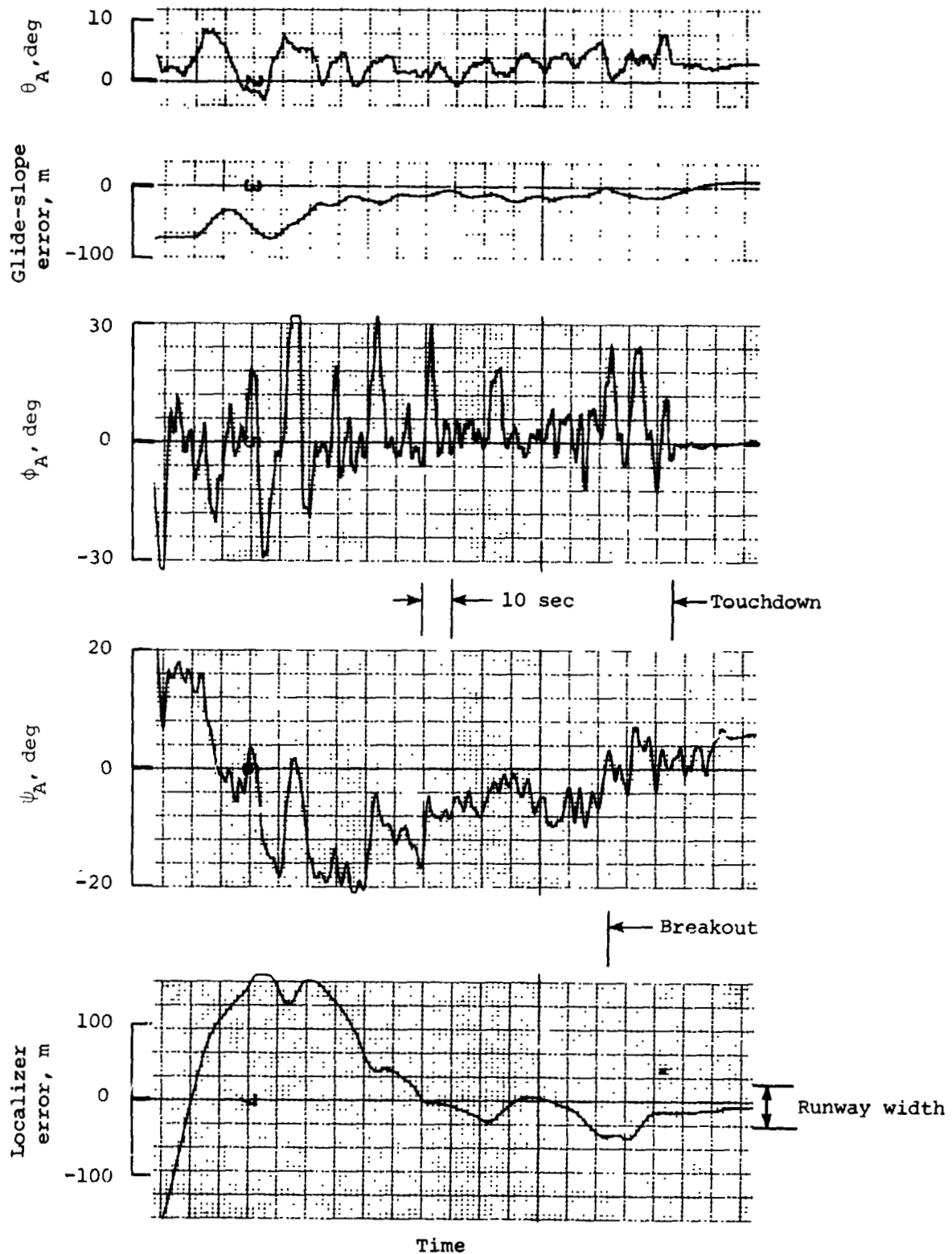


Figure 24.- Time histories of final approach using conventional HSI by subject 4. Moderate thunderstorm wind condition.